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FLOW CHARACTERISTICS IN A
TWO-DIMENSIONAL MULTIPLE-NOZZLE
MULTIPLE-DIFFUSER ASSEMBLY
THESIS
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(See 1473)

FLOW CHARACTERISTICS IN A

TWO-DIMENSIONAL MULTIPLE-NOZZLE

MULTIPLE-DIFFUSER ASSEMBLY

THESIS

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Master of Science

by

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Preface

This study was the result of continued interest
in the development of high energy lasers. The overall
requirements for this study were established by the
Air Force Weapons Laboratory, Kirtland AFB, New Mexico.
This study is a continuation of previous efforts by
Dr. A. J. Shine of the Air Force Institute of Technology.

This study was made to observe variations in start
and unstart performance in a multiple-nozzle variable
multiple-diffuser assembly. Additional information
was obtained on the variation of static pressures in
the diffuser passages, nozzle trailing edge wakes, and
nozzle center stream flows. Schlieren optical techniques
and static pressure taps were the primary means of
obtaining data.

The support and suggestions of Drs. A. J. Shine,
W. C. Elrod, H. E. Wright, and R. A. Merz were deeply
appreciated. The assistance of Mr. William Baker was
invaluable, and he recieves a special thanks. The
apparatus for this study was expeditiously provided by
Mr. M. W. Wolfe, AFIT shop forman. And finally, special
acknowledgment is extended to my wife, Wandee, whose
patience and devotion made this study possible.

<div align="right">Jeffrey L. Kiner</div>

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List of Symbols

A_{dt} Cross-sectional area of diffuser throat

A_{nt} Cross-sectional area of nozzle throat

L Distance between nozzle exit plane and diffuser entrance plane

M Mach number

P_o Stagnation pressure in stilling chamber

P_{ox} Stagnation pressure prior to a normal shock

P_{oy} Stagnation pressure after a normal shock

x Axial distance downstream from the nozzle exit plane

Abstract

Pressure measurements and schlieren photographs were used to study the flow characteristics in a two-dimensional multiple-nozzle multiple-diffuser assembly. The assembly consisted of 29 full nozzles with a half nozzle at each end of the array. The contoured nozzles were designed for an ideal exit Mach number of 3.23 . Fourteen axial diffuser vanes provided 15 diffuser passages. Flow characteristics were studied at five positions of the diffuser entrance plane with respect to the nozzle exit plane. Air at 80°F and a maximum of 118 psig was passed through the nozzles into a constant area region then through the diffusers to ambient conditions. The test cavity start and unstart pressures decreased as the diffuser entrance plane approached the nozzle exit plane. A diffuser leading edge in the immediate vicinity of a major alternate nozzle trailing edge shock intersection resulted in a flow instability during cavity start. This instability resulted in a subsonic wake in the test cavity after cavity start.

FLOW CHARACTERISTICS IN A TWO-DIMENSIONAL
MULTIPLE-NOZZLE MULTIPLE-DIFFUSER ASSEMBLY

I.   Introduction

Background

The general class of high energy lasers employs
a flowing medium as a means of producing non-equilibrium
molecular vibrational energy populations, population
inversions. The basic operation of the high energy
chemical or gas dynamic laser is the rapid expansion
of a gas through an array of very short supersonic
nozzles. Depending on the type of laser, mixing may
occur prior to or after expansion. In all cases, the
result is that the molecular vibrational energy cannot
relax rapidly enough to maintain Boltzmann equilibrium
(ref 6, 12). As these molecules relax to a stable
energy level, they may release energy in the form of
photons. This photon release is referred to as lasing.
By using optical mirrors to reflect the laser beam
through the flow field, the power of the beam is
amplified. A large amplification requires a large
population inversion which in turn requires a large
mass flow rate of the working medium (ref 9). One
method of accomplishing this is to use a large array
of closely spaced nozzles. Figure 1 is a schematic
of a high energy laser system, the gas dynamic laser
(ref 3:2).

1.
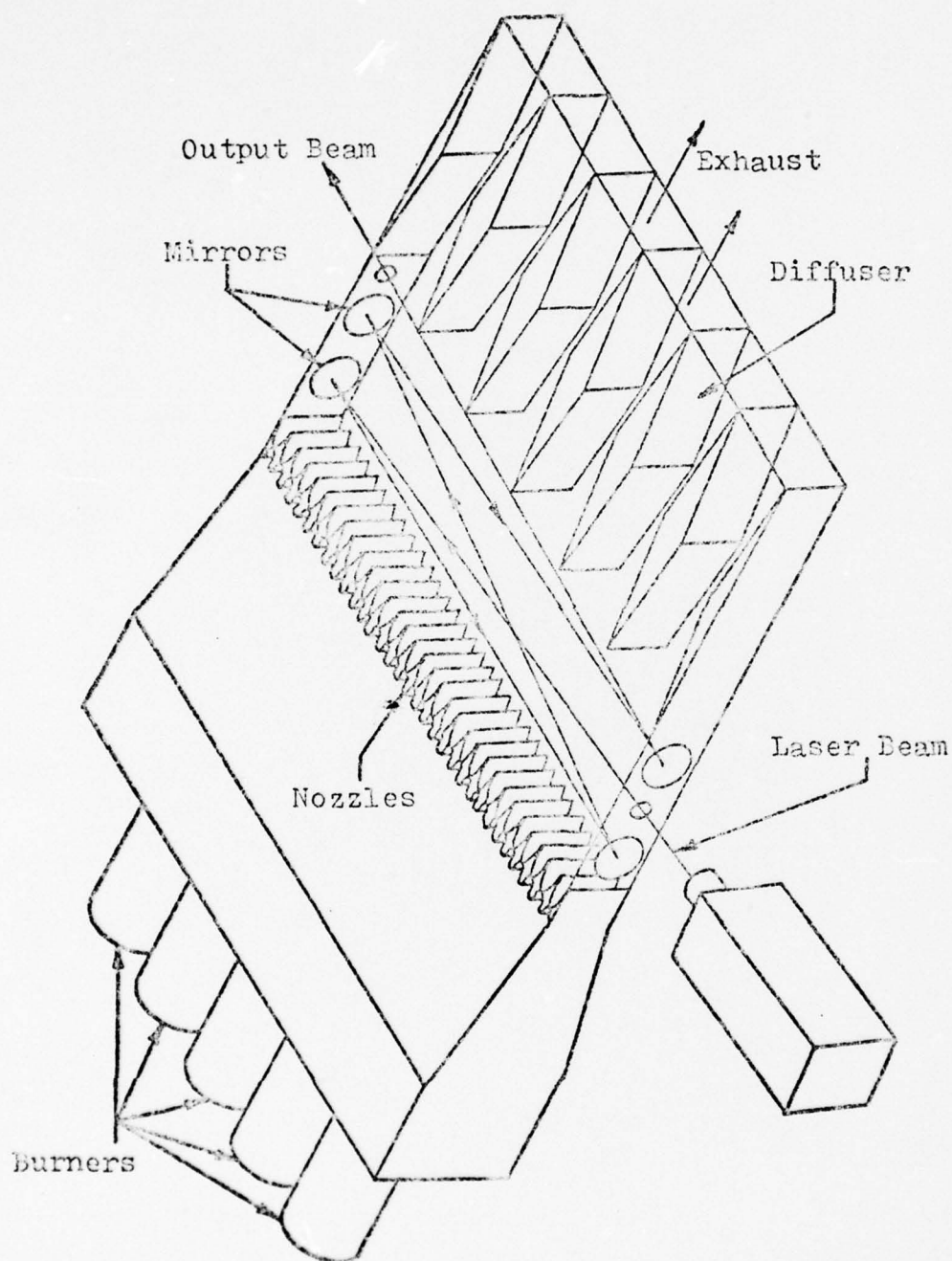
Fig. 1. Schematic of a Gas Dynamic Laser

Packaging is the primary problem facing the high energy laser as an aerospace weapon system. System mass, size, and operational power requirements tend to make starting and operation at the lowest practicable system inlet pressure a desirable feature. Low inlet pressure in turn may produce a pressure substantially below atmospheric pressure in the lasing cavity. Consequently, to discharge the flow, a diffuser or other means of increasing the pressure should be incorporated. The effectiveness with which a diffuser recovers the pressure depends on its design and pressure on the downstream side of the diffuser. Several studies (ref 2, 3, 7, 8) have been made in this area. Packaging requirements dictated that the diffuser occupy a small volume. Short diffusers in turn tend to drive system inlet pressures higher which in turn makes the system heavier. Therefore, a means of keeping inlet pressures low and diffuser volume small must be found.

The Problem

The purpose of this study was to determine if a cold flow, two-dimensional, multiple nozzle-diffuser assembly could be started and maintain stable operation at lower inlet pressures in an assembly with a variable diffuser entrance plane than in an assembly with fixed diffuser vanes. It attempted to show that as the

distance between the diffuser entrance plane and
nozzle exit plane decreases, the required starting
pressure decreases. It further attempted to show
that some of these lower starting pressures were
within the stable pressure range of the system in its
steady state operational configuration.

Scope

In support of this study, the following objectives
were met: (1) move the diffuser entrance plane to
five specific locations with respect to the nozzle exit
plane, L; (2) determine minimum starting pressure at
each location of the diffuser entrance plane; (3)
determine the minimum operating pressure of the test
cavity at each of the diffuser entrance plane positions;
and (4) determine static pressure variations in the
streamwise direction at several locations in the test
cavity and diffuser. This study did not address:
(1) variation of specific heats; (2) boundary layer
control; (3) boundary layer effects in the flow field;
(4) variation of inlet temperature; nor (5) variation
of diffuser exit conditions.

Variable Position Multiple Diffuser Defined

Variable position is defined as a series of steady
state positions of the diffuser entrance plane with
respect to the nozzle exit plane in the streamwise

direction.

Started Test Cavity Defined

Started test cavity is defined as the condition of steady state supersonic flow in the entire region between the nozzle exit plane and the diffuser entrance plane, the cavity.

Assumptions

Air was assumed to behave as an ideal gas. The ratio of specific heats was assumed to remain at a constant value of 1.40 . All nozzle inlet pressures were assumed equal. One-dimensional, steady, adiabatic, inviscid flow was assumed throughout the entire assembly after the cavity starts. The nozzles were assumed isentropic. Flow patterns in the test model were assumed similar to those in an actual high energy laser under operating conditions. The flow conditions at the five specific positions of the diffuser entrance plane were assumed identical to those in a continuously variable diffuser entrance plane at these same locations. The location of the diffuser entrance plane at $L = 1.333$ inches was assumed to be the steady state operating point of both a variable position and fixed diffuser system.

General Approach

Flow characteristics were determined at five specific locations of the diffuser entrance plane with respect to the nozzle exit plane from 0.000 inches to 1.333 inches in 0.333 inch increments in the streamwise direction. Schlieren optical methods were utilized to determine the flow pattern in the test model. The schlieren assembly was perpendicular to the flow direction. The nozzle exit plane, test cavity, and entire diffuser region were visible in the schlieren photographs. One set of five static pressure taps measured pressure variation in the streamwise direction along an axis coincident with the centerline of a nozzle. A second set of 11 pressure taps measured the pressure variation in the streamwise direction along an axis coincident with the centerline of a diffuser passage. Stilling chamber stagnation pressure was recorded at start and unstart of the test cavity.

The following test conditions were held constant throughout the study: (1) the geometry of the nozzles and diffusers; (2) the geometry of the diffuser vanes with respect to each other remained constant; (3) a thirty nozzle assembly was used for the entire study; (4) a fifteen diffuser assembly was used for the entire study; and (5) diffuser exit pressure remained ambient for all tests.

II. Apparatus

The arrangement of the apparatus used in this study is shown in Fig 2 .

Test Cavity

The test cavity was 8.1 inches wide, 9.95 inches long, and 0.375 inches across. The external sidewalls were constructed of o.75 inch thick clear plexiglass and measures 11.1 inches in width. The plexiglass endwalls were 0.375 inches thick, and each was 1.50 inches wide. The nozzle bank consisted of 30 nozzles, 29 full nozzles and a half nozzle at each end of the test cavity. The diffuser bank consisted of 15 axial diffusers. The nozzles and diffusers were numbered from left to right with respect to a reference mark on the test assembly base plate, shown in Fig 3 . The test section used for this study is depicted in Fig 4 and is shown in Fig 5 .

Nozzles

The nozzle walls were constructed of o.375 inch thick plexiglass. They were contoured and designed by the method of characteristics for an ideal exit Mach number of 3.23 . Figure 6 illustrates the basic nozzle design parameters.

1. Compressor and dryer
2. Storage tank
3. Flow control valve
4. Filters and screen
5. Chamber pressure tap
6. Stilling chamber
7. Test section
8. Static pressure taps
9. Static pressure manometer boards
10. Manometer data camera
11. Zirconium arc lamp
12. Spark lamp
13. Plane mirror
14. Parabolic mirror
15. Knife edge
16. Focal plane
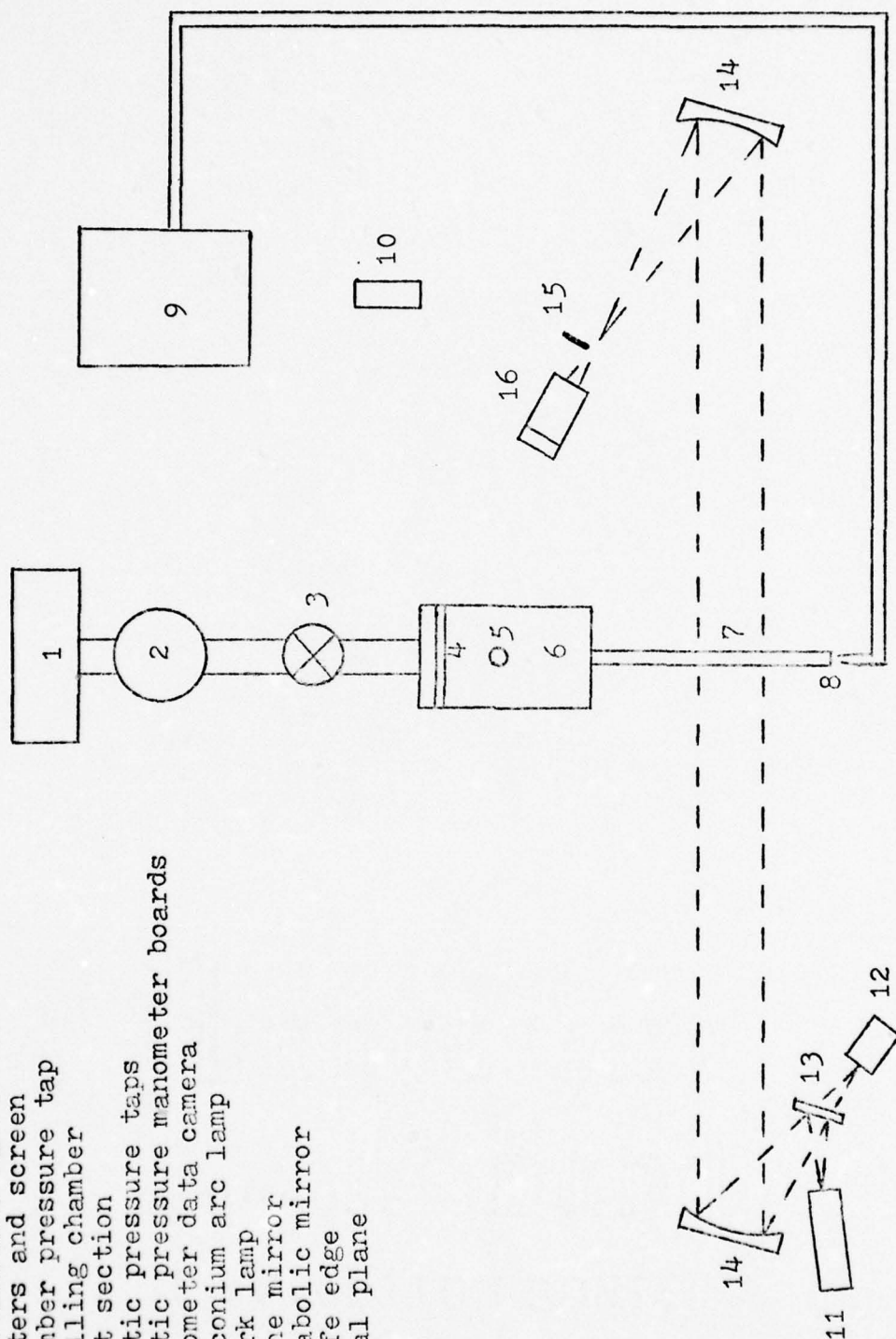
Fig. 2. Test Facility Schematic

8.

reference
mark

nozzle/diffuser numbering
proceeds in this direction
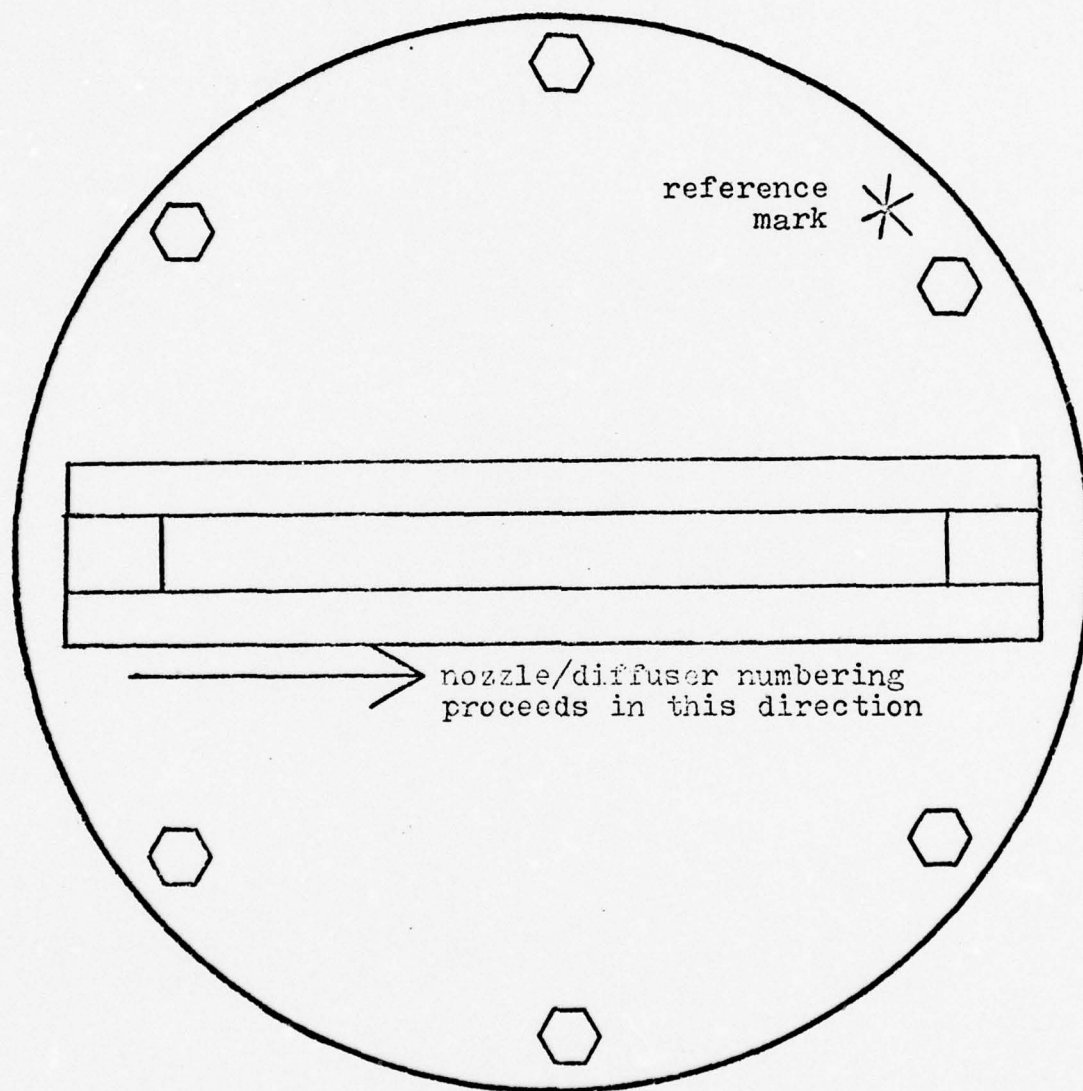
Fig. 3. Top View of Test Assembly

9.
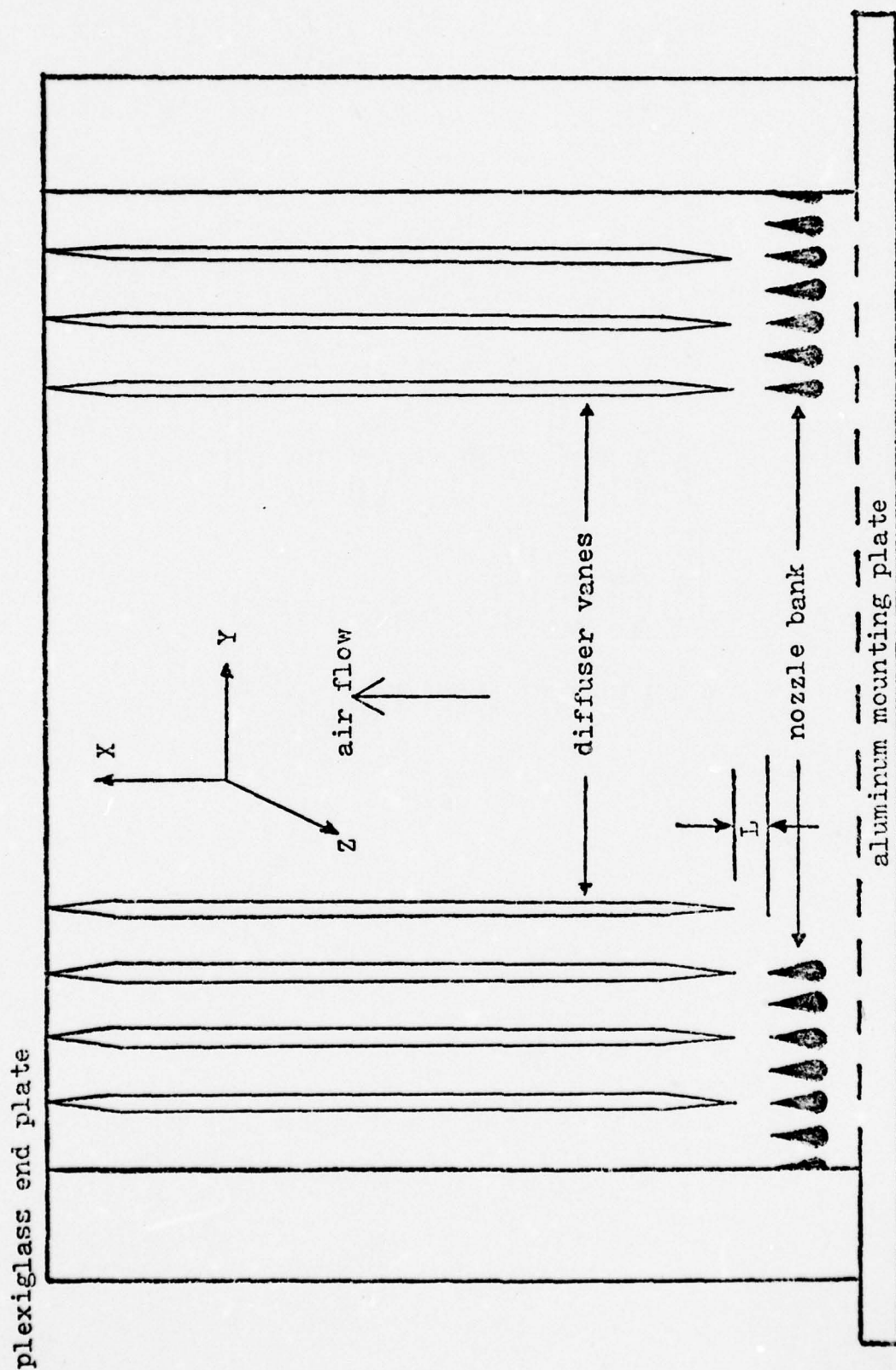
Fig. 4. Schematic of Test Section

10.
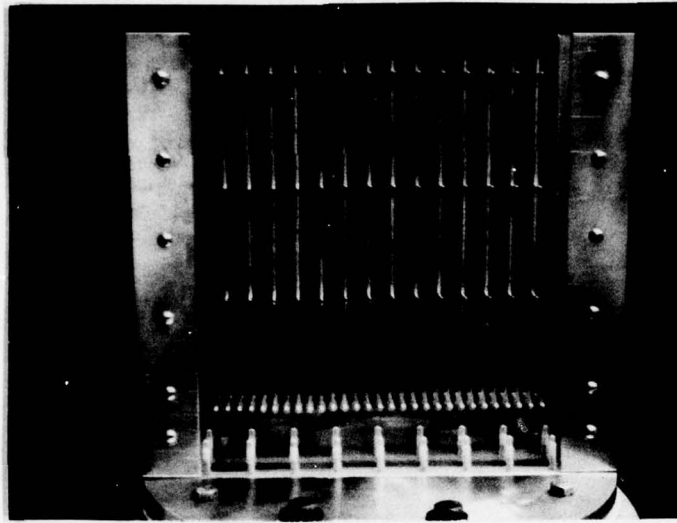
Fig. 5. Test Cavity in Vertical Position

Diffuser Design

As can be seen in Fig 4 , the diffuser vanes were arranged such that their leading edges were goemetrically alligned along the axes of alternate nozzle trailing edges, providing one diffuser passage per two nozzle flow streams. The minimum diffuser area must be capable of passing a normal shock with a total pressure ratio as determined by the nozzle exit Mach number. The relationship between the total pressure ratio across the shock and the nozzle and exit throat areas is (ref 1:20, 11:144):

$$\frac{A_{nt}}{A_{dt}} = \frac{P_{oy}}{P_{ox}} \tag{1}$$

The total pressure ratio was obtained from normal shock

11.
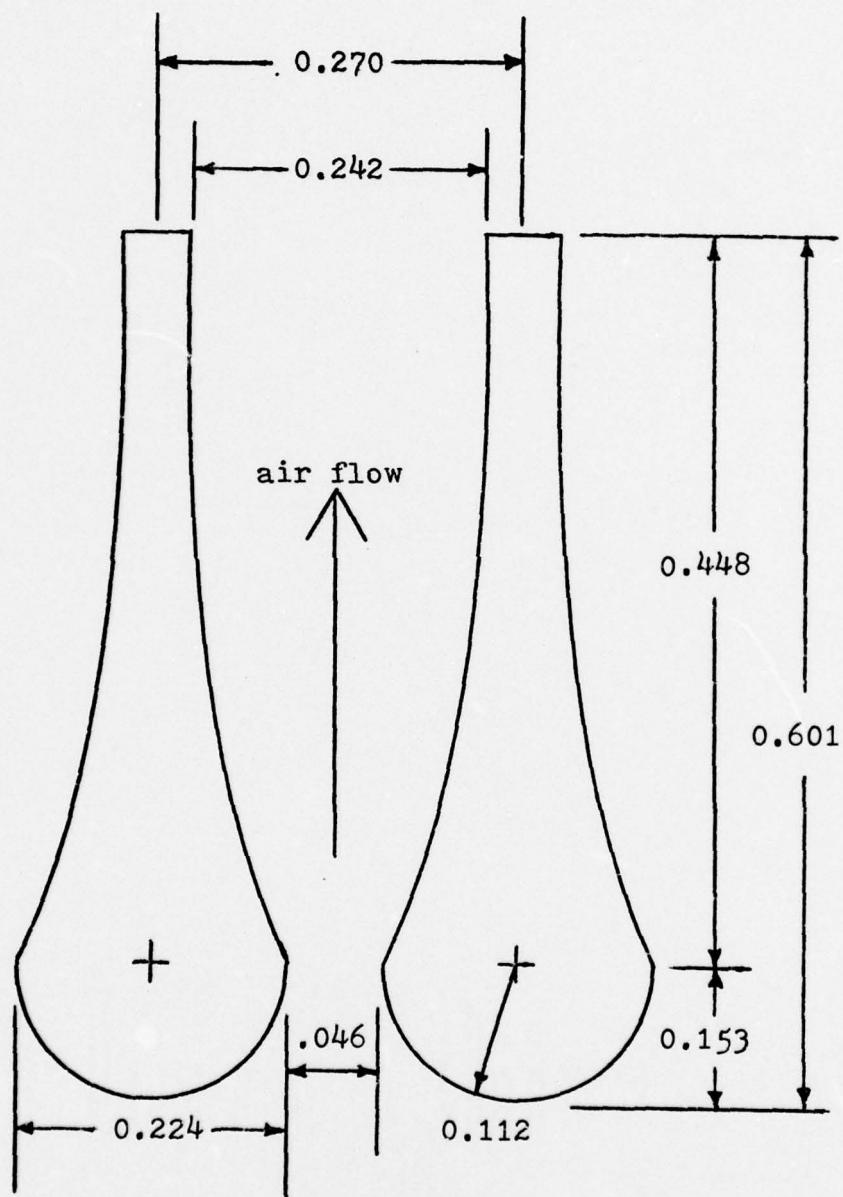
Dimensions shown in inches

Fig. 6. Mach 3.23 Contoured Nozzle

tables (ref 4) corresponding to an entrance Mach number of 3.23 . The resulting ideal minimum diffuser width was 0.342 inches. As will be discussed in section IV, the diffuser passage width was enlarged to 0.400 inches.

The diffuser vanes were constructed of aluminum 0.375 inches thick. The vanes were originally 0.199 inches and later reduced to 0.140 inches wide. The vanes had a leading edge half angle of five degrees and a trailing edge half angle of six degrees. Total vane length was 6.719 inches. Diffuser dimensions are shown in Fig 7 .

Schlieren Optical System

A schematic of the schlieren optical system is shown in Fig 2 . This system used a steady zirconium arc lamp light source and a frosted glass screen at the focal plane for real time flow observations. The system used a 1/6 microsecond spark lamp as the light source and a (4 x 5) inch format Polaroid graphic camera at the focal plane for recording photographic results. Polaroid film, type 47 , was used for photographic results. All photographs were taken with the knife edge perpendicular to the flow direction. The parabolic mirrors used were 16 inches in diameter with a 72 inch focal length.

air flow

6 degree
half angle

5 degree
half angle

0.400

5.0

6.719

0.140

0.540
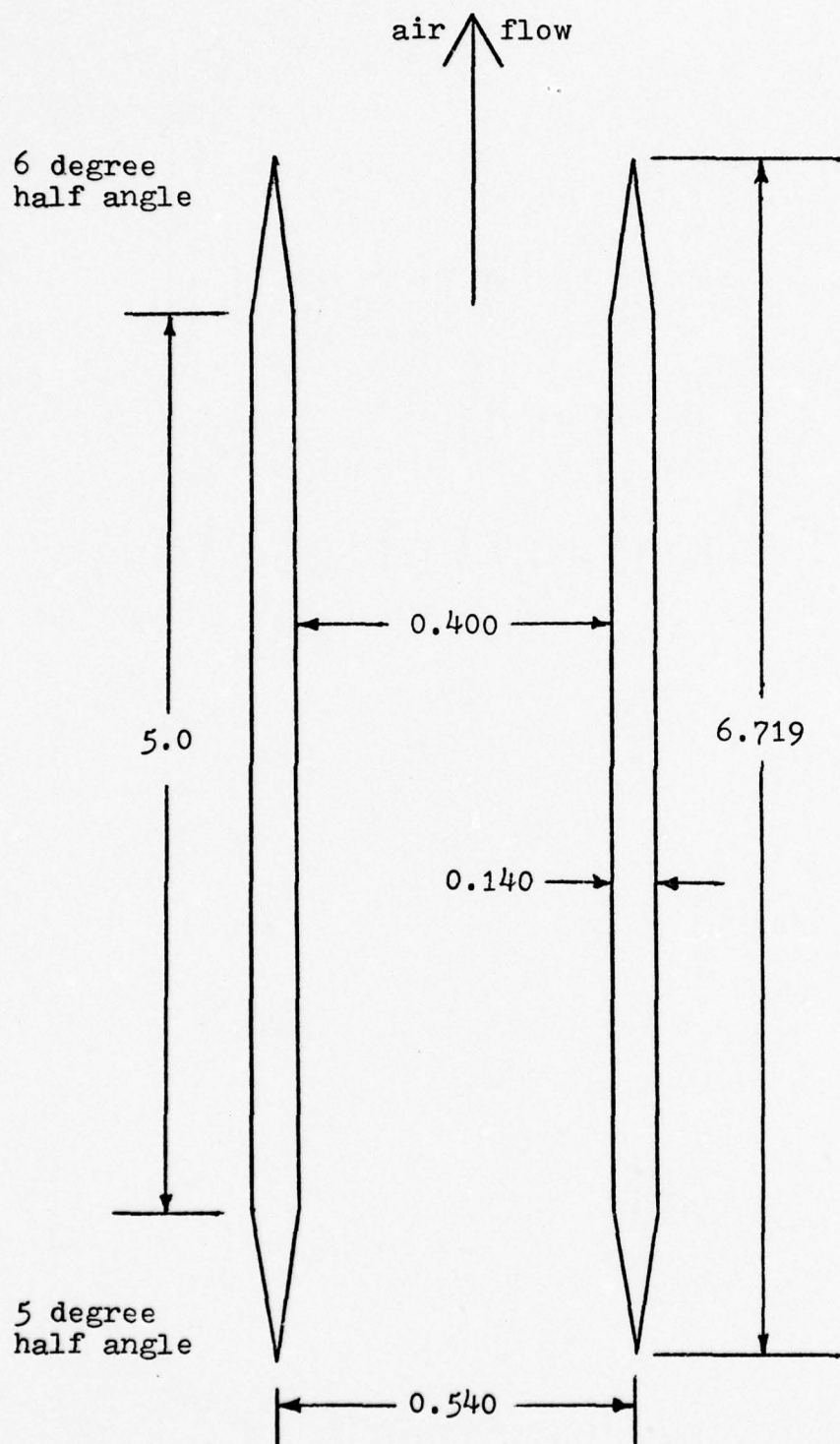
Dimensions shown in inches

Fig. 7. Diffuser Design Parameters

14.

Instrumentation

A 0-200 psig dial gage was located in the air supply line upstream of the supply control valve. This gage had an accuracy of $\pm$ 1.0 psi . The stilling chamber pressure was measured on a 0-100 psig dial gage physically located on one of the manometer boards. This gage had an accurecy of $\pm$ 1/2 psi . Static pressure measurements were obtained through taps in the test section's rear plexiglass sidewall. These taps were arranged in two series. The first series, numbers 1-5 , was geometrically located on the centerline of nozzle number 16 . This series is shown in Fig 8 . The second series, numbers 6-16 , was geometrically located on the centerline of diffuser passage number 5 . This series is depicted in Fig 9 . Static pressures were measured on 50 inch U-tube manometers. The manometers, which were scaled in 0.10 inch increments, were mounted vertically. They contained mercury as the working fluid and the free end was exposed to ambient conditions. The stilling chamber pressure and all static pressures were recorded simultaneously at each data point. This was accomplished by a tripod mounted (4 x 5) inch format Polaroid grapgic camera using type 42 Polaroid film.
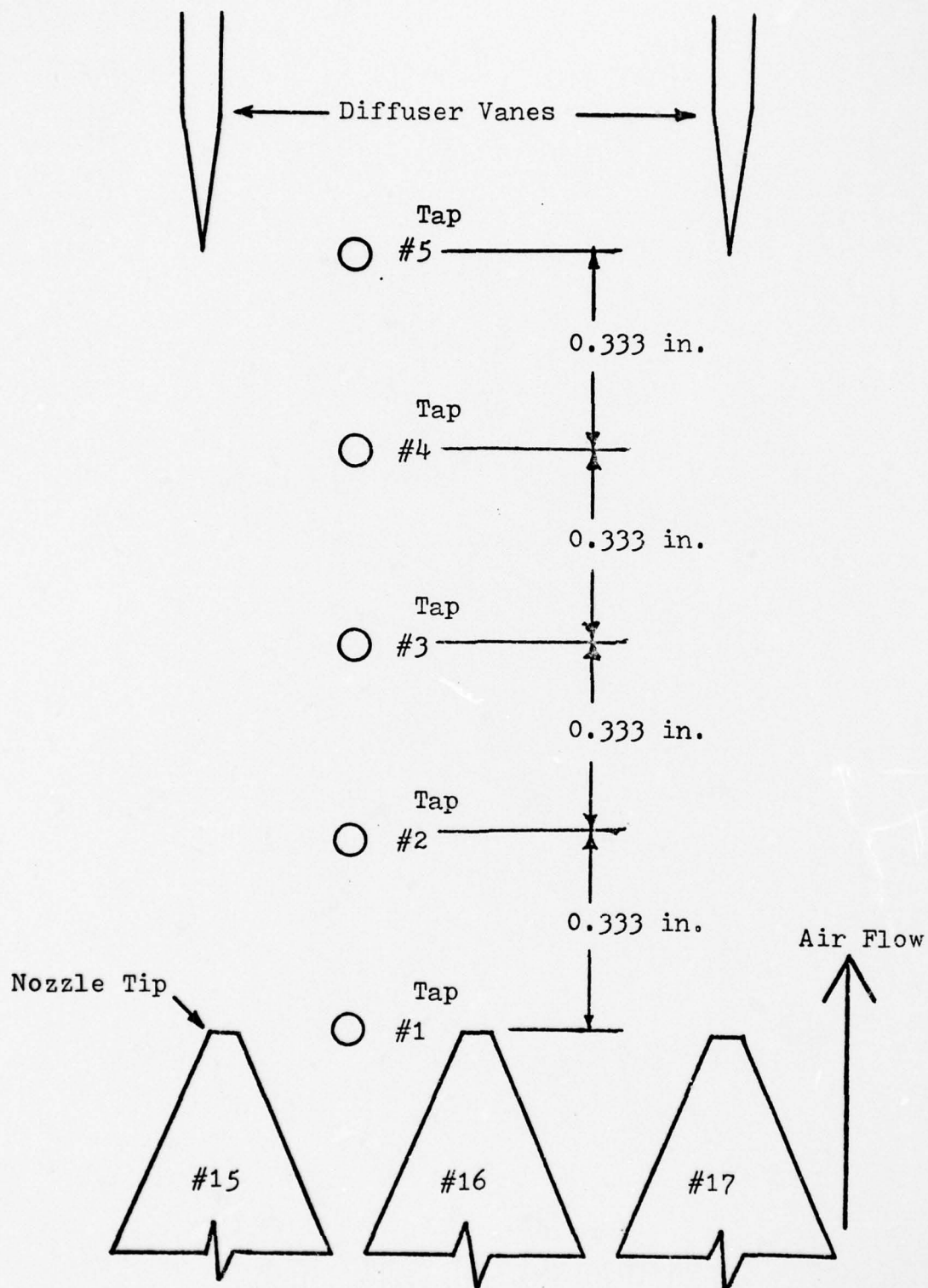
Fig. 8. Center Nozzle Pressure Tap Locations
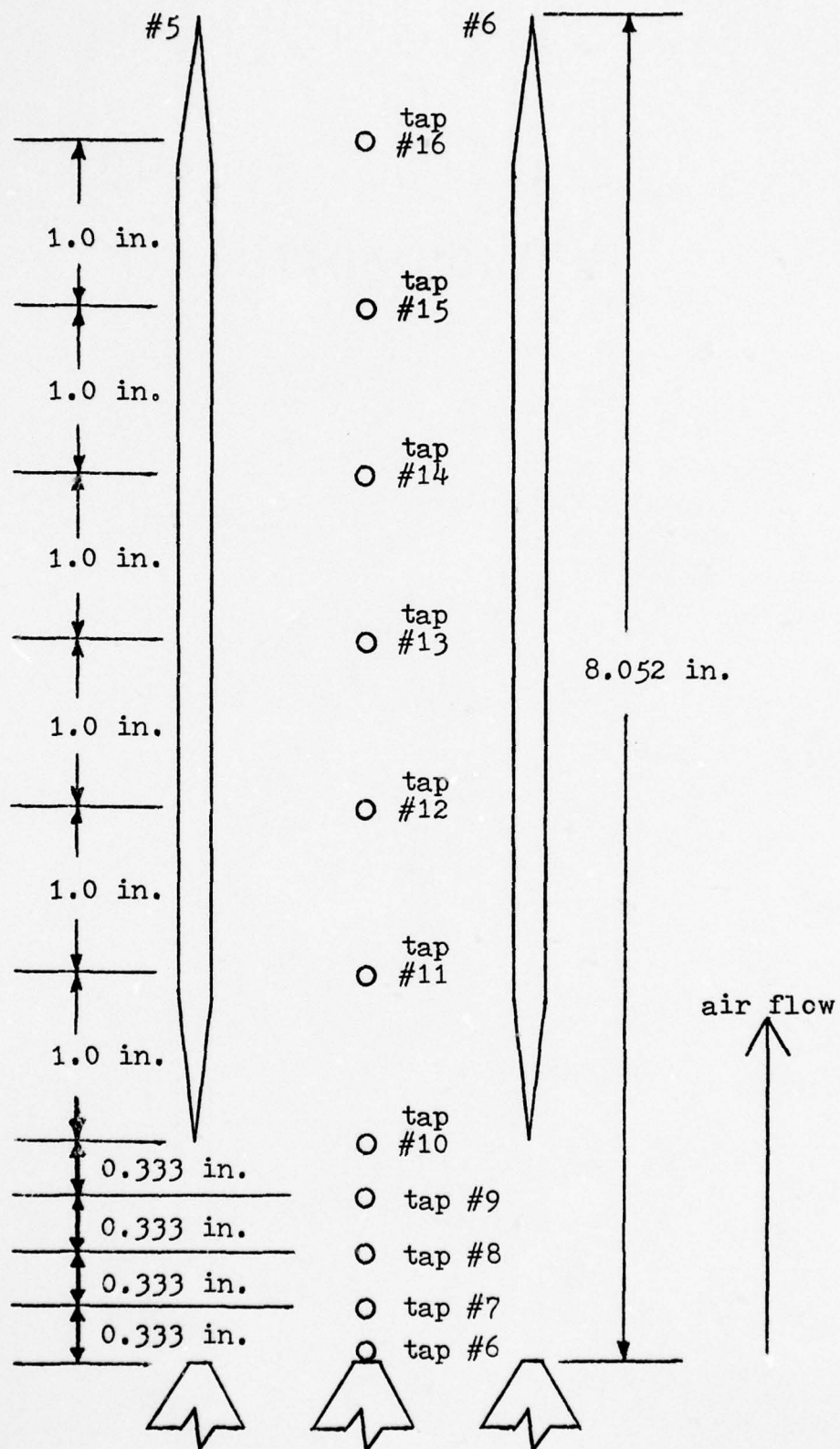
Fig. 9. Center Diffuser and Wake Pressure Tap Locations

III. Experimental Proceedure

The test section was configured with the desired
nozzle-diffuser separation. The schlieren was configured
for continuous viewing, and the manometer boards were
positioned for optimum viewing. The flow control valve
was slowly opened, and the stilling chamber pressure
was recorded at cavity start. The flow control valve
was then slowly closed, and the stilling chamber pressure
was recorded at unstart. Several test runs were conducted
to accurately determine the start and unstart pressures.

The schlieren was then reconfigured to obtain
photographs of the flow field. At each position of the
diffuser, a minimum of five schlieren photographs were
taken to assure accuracy of flow field data.

The manometer boards were realligned to obtain
optimum photographic results. All manometer values
were instantaneously recorded on Polaroid film. Several
pictures were taken at each data point to assure
repeatability of data.

The compressor supplied a maximum of 118 psig
which corresponds to a maximum mass flow rate of
0.55 Lb_m/sec . The test cavity was capable of handling
much higher flow rates, and as a result, the stilling
chamber pressure bled off rapidly above 75 psig and
slowly below 65 psig . This provided some difficulty in
determining starting pressures. However, this was

18.

beneficial because the system could be taken to a
higher than desired data point pressure. Then as
line pressure bled off, pictures were obtained of the
manometer boards at the desired pressure. By doing
this, starting transients were completely dampened out
of the manometers. This also allowed the experimenter
to move freely about and closely observe the flow
field. Hence, any anomalies in the flow field could
readily be detected. The rate of pressure decrease
was slow enough that disturbances were not induced
in the flow field.

IV. Discussion and Results

The purpose of this study was to determine if a
variable diffuser assembly could start and maintain
stable operation at inlet pressures lower than those
in a comperable fixed diffuser assembly. In consideration
of this purpose, the following items are discussed.

Diffuser Throat Area

As mentioned in section II, the design throat
area for the diffuser yielded a 0.342 inch passage
width. At this design point, the assembly would not
start at L = 1.333 inches and 100 psig stilling chamber
pressure, peak pressure available. The diffuser vanes
were uniformly reduced in width in 0.002 inch increments.
At a passage width of 0.400 inches, the assembly
consistantly started at the same pressure, 82 psig .
Figure 10 shows the cavity fully started at this position.
Diffuser parameters were not further altered for the
remainder of this study.

Diffuser Plane Positions

The diffuser entrance plane positions relative
to the nozzle exit plane, L, are shown in Fig 11 .
Position one corresponds to the steady state operating
point of this assembly, the diffuser plane position
during continuous operation of the assembly. This was

Fig. 10. Schlieren Photograph of Fully Started Test
Cavity, L = 1.333 inches, P_o = 82 psig

also the fixed diffuser reference position of the test
assembly. At position five, the diffuser leading
edges were in contact with their corresponding nozzle
trailing edges. The diffuser vanes were physically
bolted to the assembly sidewalls at each position.
In changing the diffuser position, L was consecutively
reduced by 0.333 inches.

Start-Unstart Performance

The start and and minimum operating pressures at
each diffuser plane position are shown in Fig 12 .
The difference in starting pressures between positions
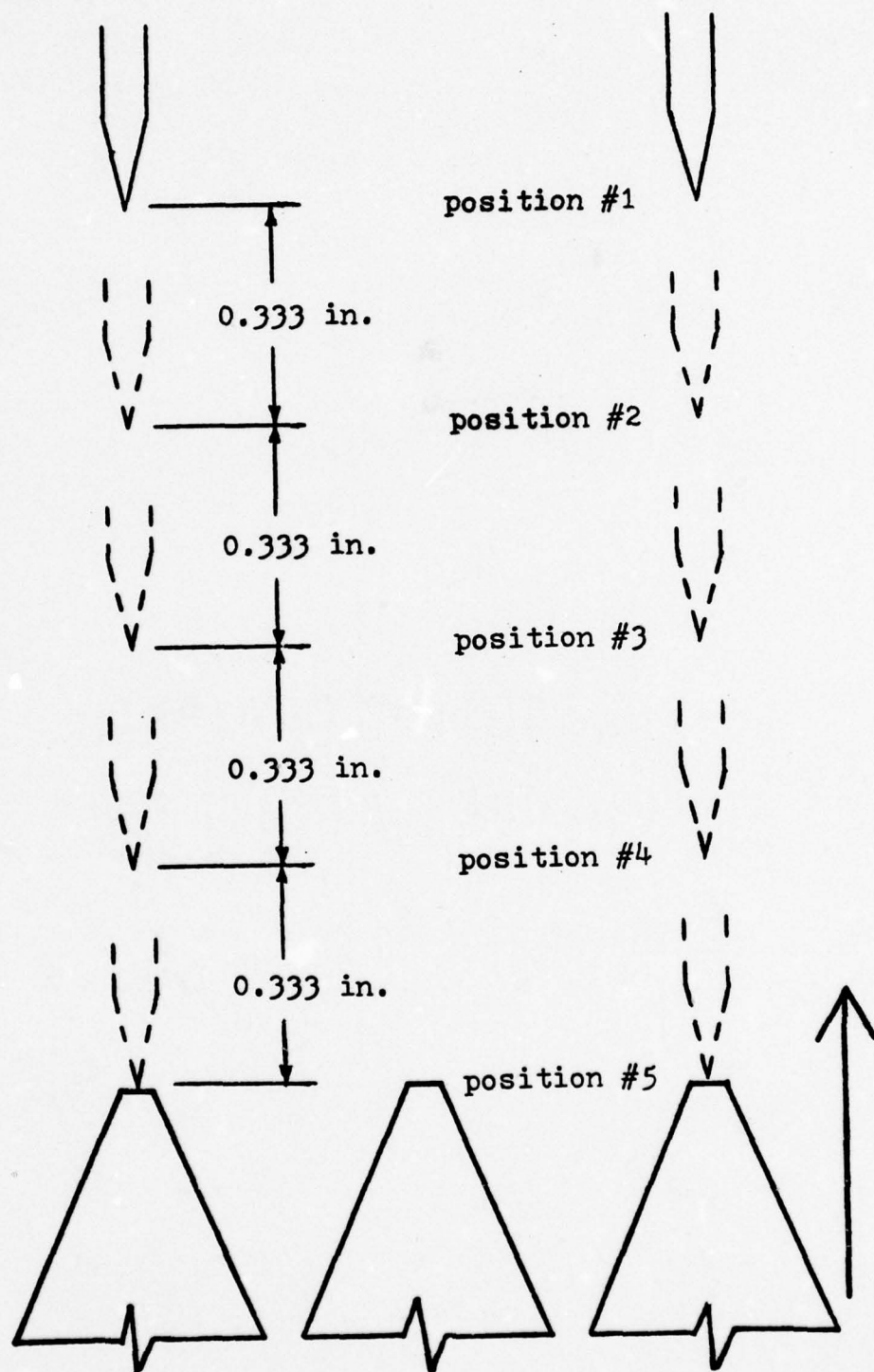one and five was 35 psig . The greatest reduction in

21.

Fig. 11. Diffuser Plane Positions
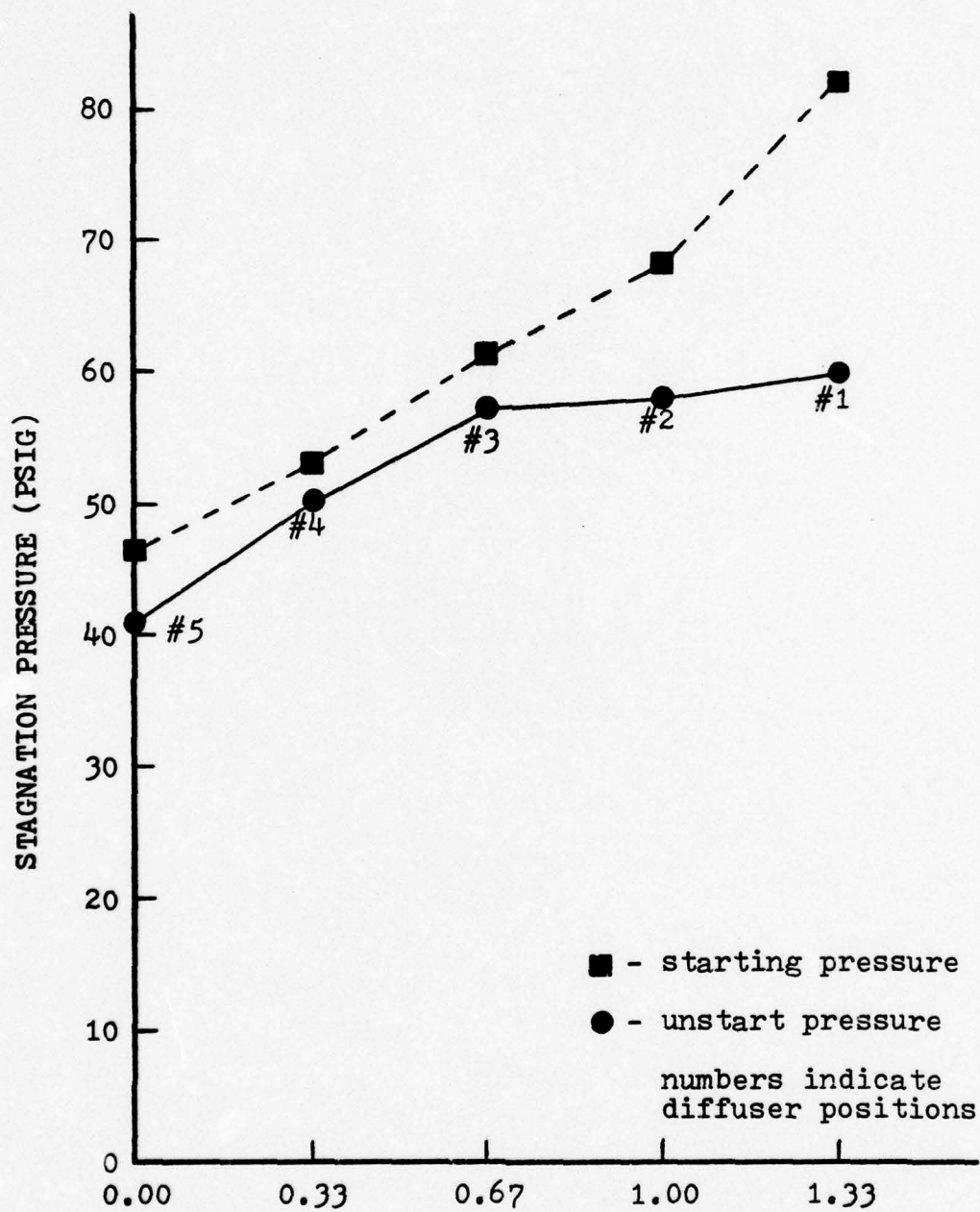
Fig. 12. Variation of Start/Unstart Pressures with L

starting pressure was observed between positions one and two. The reduction in unstart pressure was 18 psig between positions one and five. The greatest pressure reduction occurred between positions four and five. Once started, system operation was stable at pressures between the start and unstart pressures. A stable operating range of 22 psig was observed at position one between the start and minimum operating pressures. This operating range was reduced to 2 psig at position four. The system maintained stable operation at all available pressures greater than the minimum starting pressure.

At position two, the diffuser leading edges were in the immediate vicinity of the intersection of alternate nozzle trailing edge shocks. The region is circled in Fig 13 . At this position, the entire wake flow of nozzle vane number 20 remained subsonic after the assembly was started for 50 per cent of the test runs. Figure 14 depicts this subsonic wake. At the same time, the remainder of the system consistantly started. Operation of the system was stable and remained stable as line pressure was decreased to system unstart. System start and unstart pressures were the same for all test runs at this position. This phenomenon appeared to be a function of the geometric position of the diffuser leading edge relative to the shock intersection. Comparison of schlieren photographs

region of interest

shock
waves

expansion
waves

air
flow

Fig. 13. Shock Expansion Pattern at Nozzle Trailing Edge

25.

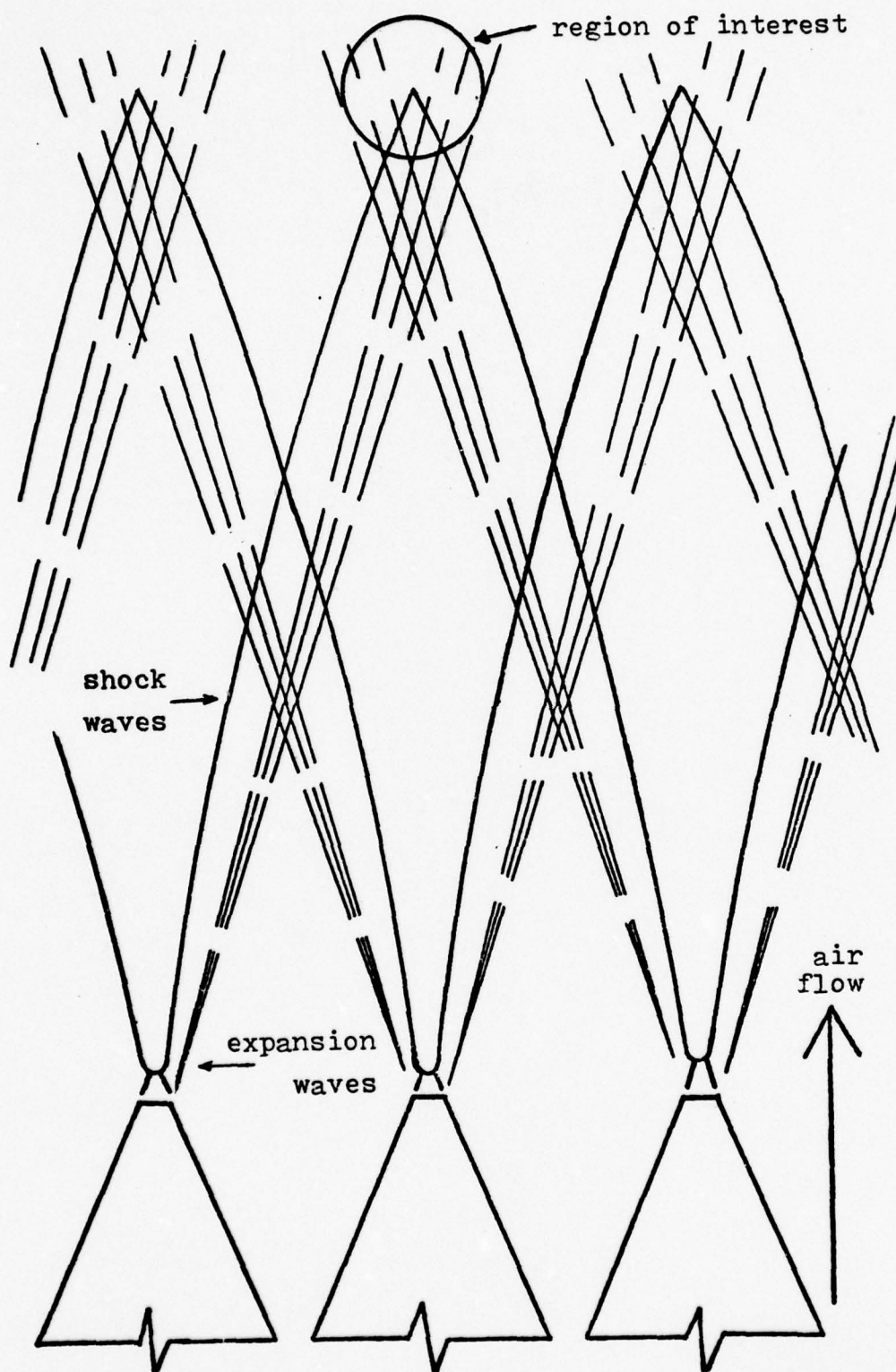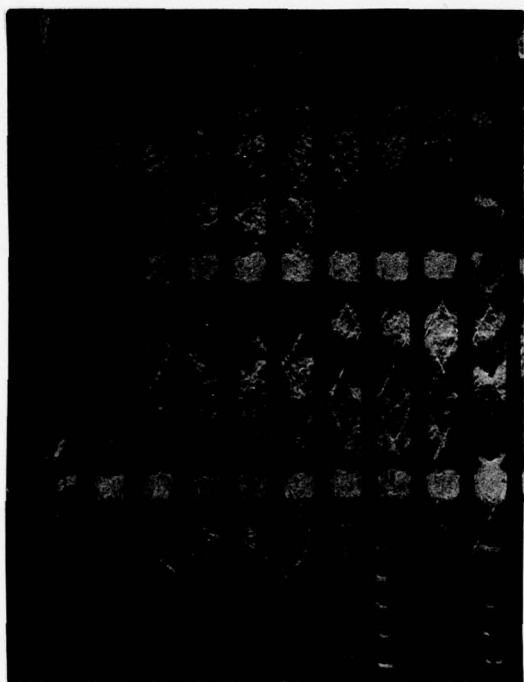Fig. 14. Schlieren Photograph of Subsonic Wake from
Nozzle Vane Number 20 , L = 1.000 inches, P_o = 68 psig
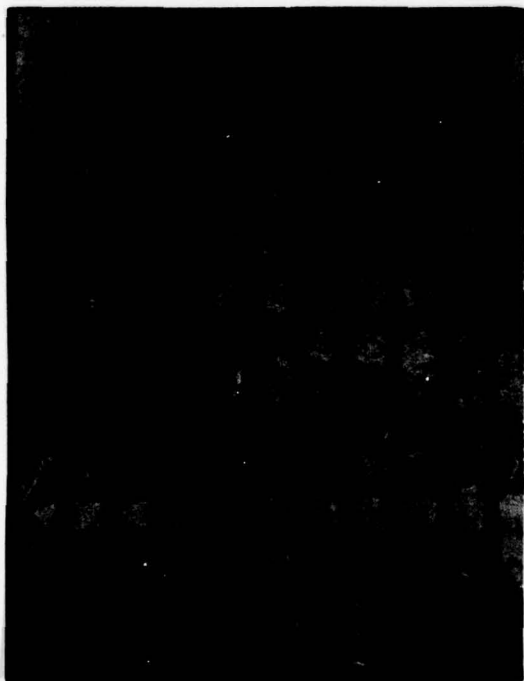
Fig. 15. Schlieren Photograph of Full Cavity Start,
L = 1.000 inches, P_o = 68 psig

26.

taken when this phenomenon did and did not occur
(Fig 14 and Fig 15), show that all of the diffuser
vanes except number 10 were slightly offset to one
side of the shock intersection. At diffuser vane
number 10 , they intersect precisely at the leading
edge. During cavity start, the ability of this inter-
section to initially stabilize was the determining
factor in whether this wake remained supersonic or
subsonic. Hence, to assure a stable cavity start, the
diffuser leading edges should not be in the immediate
vicinity of major shock intersections.

All nozzle inlets were exposed to the same uniform
stilling chamber flow conditions. Flow perturbations
were not introduced to the stilling chamber to study
their effect upon the starting performance.

Static Pressure Variation in the Diffuser

The type diffuser used for this study is classically
referred to as a normal shock diffuser (ref 5:130,
11:144). However, schlieren photographs reveal only
oblique shocks and a region of transition. This region
of transition is a wide region of varying density
gradient and is clearly visible in Fig 10, 14, and 15 .
Flow entering the region was supersonic, and flow
exiting the region was subsonic. Pressure data, as
shown in Fig 16, 17, 18, 19, and 20 , shows a region of
decreased pressure, or at least a pressure plateau at

27.
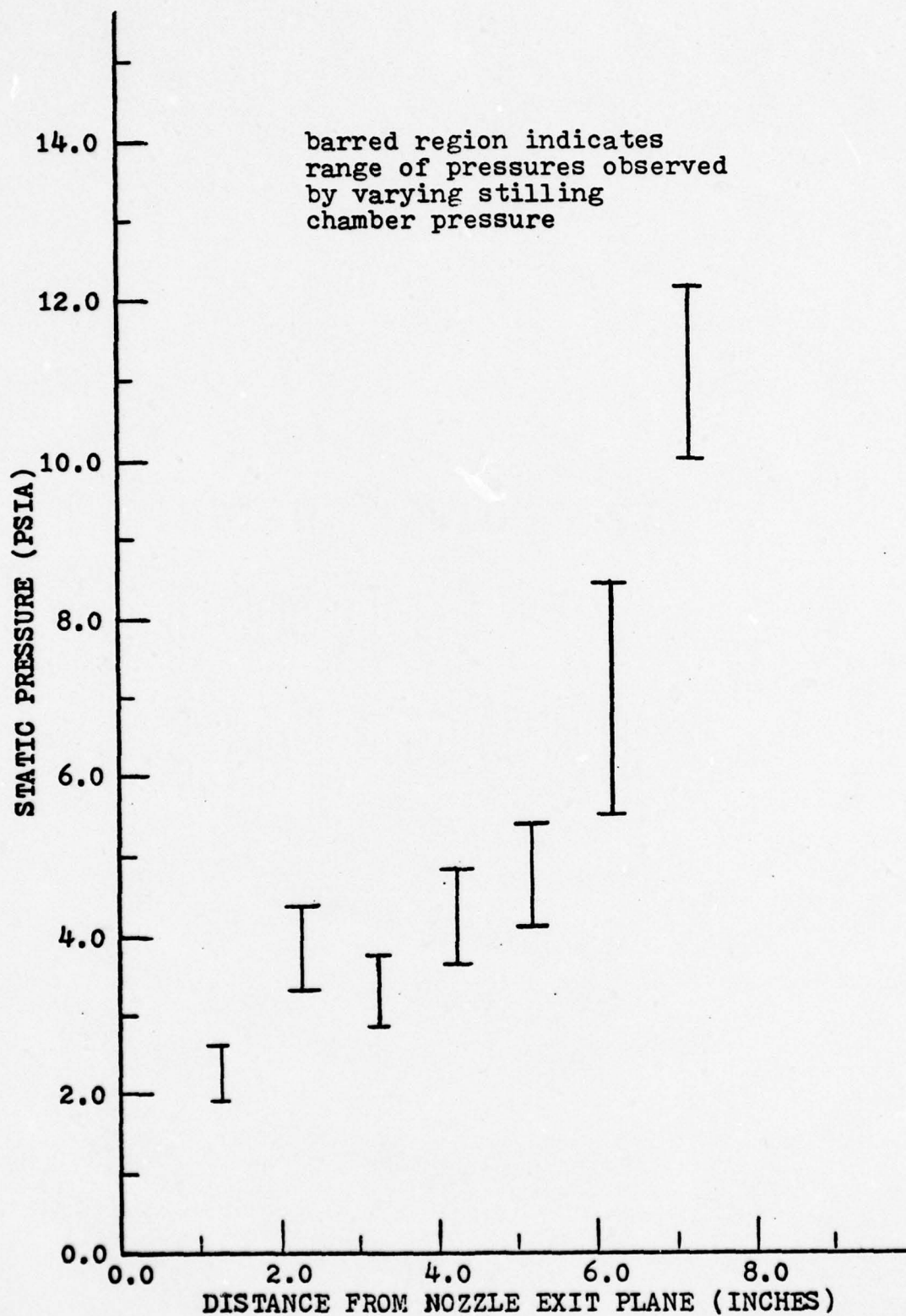
Fig. 16. Diffuser Static Pressure Variation, L = 1.333 in.

28.
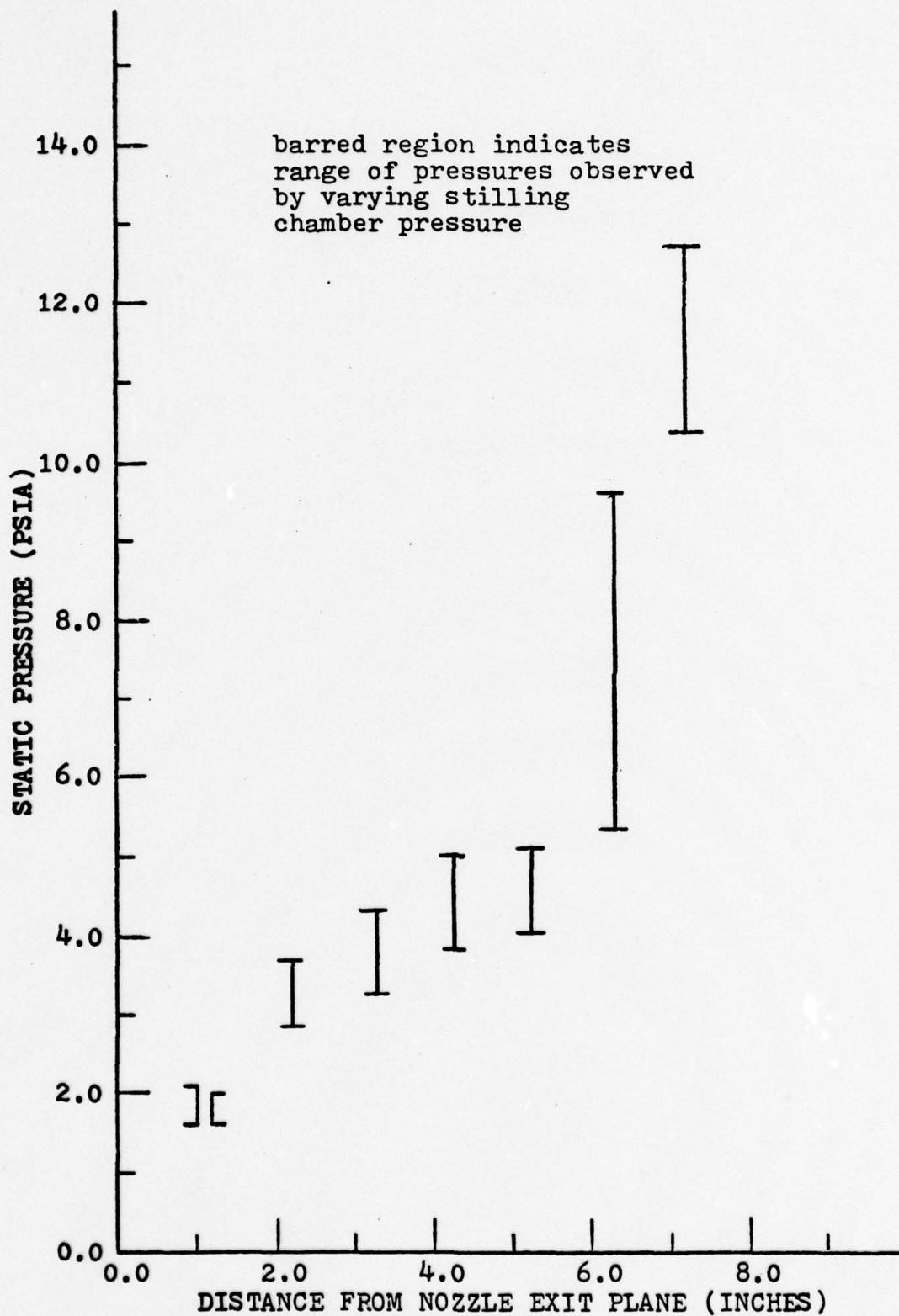
Fig. 17. Diffuser Static Pressure Variations, L = 1.000 in.

29.
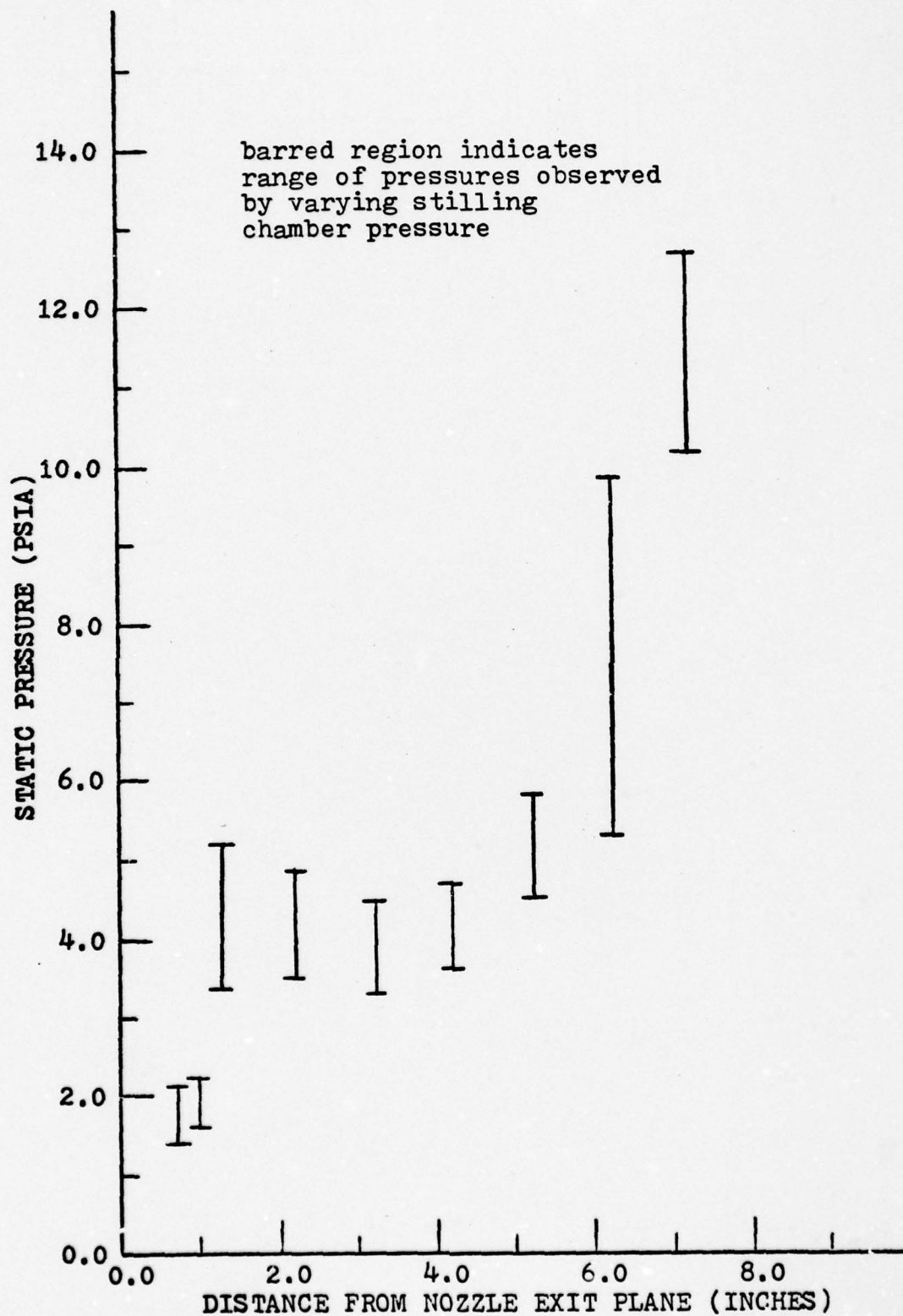
Fig. 18. Diffuser Static Pressure Variations, L = 0.667 in.
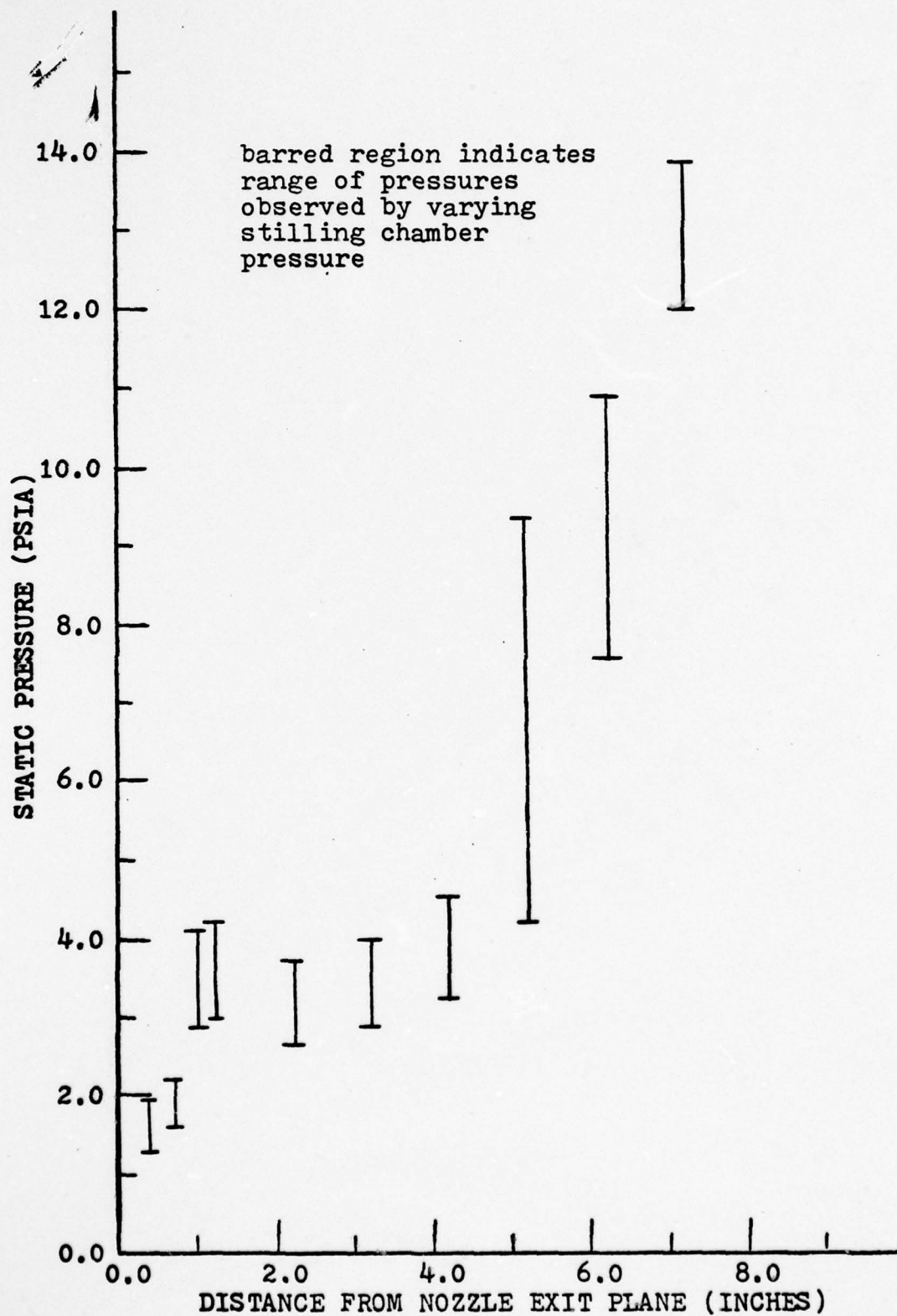
Fig. 19. Diffuser Static Pressure Variations, L = 0.333 in.
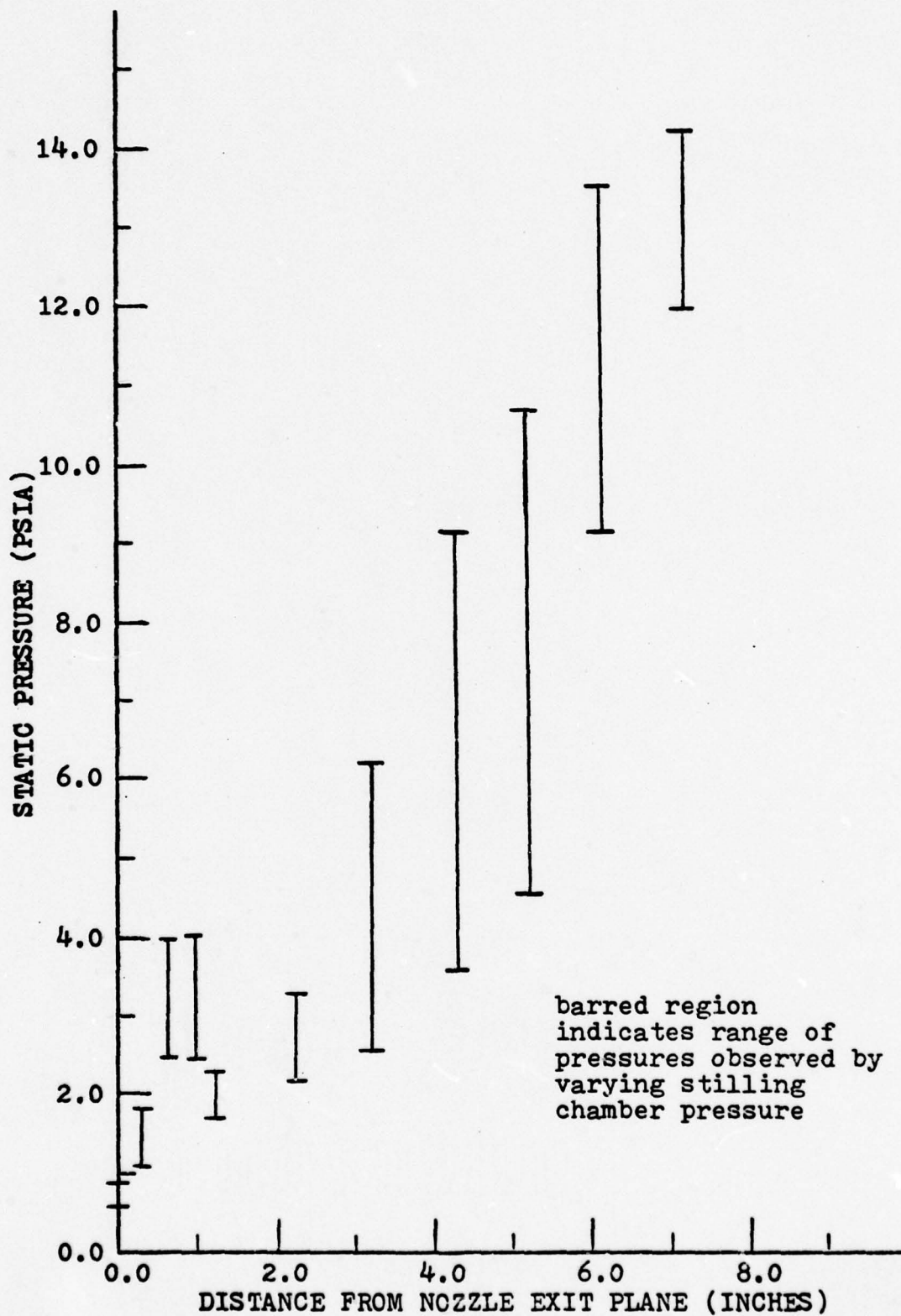
Fig. 20. Diffuser Static Pressure Variations, L = 0.000 in.

32.

L = 1.000 inch, in the diffuser passage. (Additional
pressure data is shown in appendix A.) The reason
for this was that the flow passed through a Prandtl-
Meyer expansion emanating from the inlet corner of
the diffuser vanes. If this phenomenon could be
eliminated or its effects reduced, the starting pressure
probably could be lowered, and the diffuser length
could be shortened.

V. Conclusions and Recommendations

As a result of this study, the following conclusions and recommendations have been made.

Conclusions

1. A test cavity with a variable position diffuser started and maintained stable operation at significantly lower pressures than did the same assembly using a fixed diffuser.

2. The stagnation pressure required to start the test cavity was reduced as the diffuser entrance plane approached the nozzle exit plane.

3. The minimum operating pressure of the test cavity was also reduced as the diffuser entrance plane approached the nozzle exit plane.

4. Once started, operation of the rest cavity was stable at all pressures greater than the minimum operating pressure.

Recommendations

1. A study of boundary layer growth in the diffuser passages would be of interest. It is possible that limited use of boundary layer control in the diffuser could significantly reduce the stagnation pressure required to start the test cavity.

2. Other geometric configurations of the diffuser

should be studied to determine which configuration
yields the best pressure recovery in the shortest
length. In a study of this nature, the number of
nozzles and the distance between the nozzle exit plane
and diffuser entrance plane should remain constant.

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Appendix A

Axial Variation of Static Pressure in Nozzle Trailing

Edge Wakes, Nozzle Center Streamline, and Diffuser

Center Streamline

Axial Variation of Static Pressure in Nozzle Trailing Edge Wakes, Nozzle Center Streamline, and Diffuser Center Streamline

The following tables and figures show static pressure variations, in psia, in the nozzle center streamline, nozzle trailing edge wakes, and diffuser center streamlines. Each table and figure displays data at one value of L only. Data is shown as a variation of stilling chamber pressure (psig) versus streamwise distance, x (inches), at the specified value of L . All data displayed was obtained from a steady state fully started test cavity. All manometer readings were repeatable $\pm$ 0.05 inches of mercury. Each bar in Fig 21-26 indicates the range of static pressures obtained at a particular pressure tap by varying the stilling chamber pressure and holding L constant. Figures 16-26 graphically represent data shown in tables I-V .

Table I

Static Pressure Variation in the Test Cavity

$L = 1.333$ in.

tap #	60	65	70	P_o (psig) 75	80	82
1.	1.779	1.779	1.877	2.049	2.417	2.147
2.	1.189	1.263	1.337	1.410	1.533	1.508
3.	1.459	1.558	1.680	1.779	2.000	1.852
4.	1.435	1.582	1.680	1.828	1.926	1.950
5.	1.263	1.386	1.459	1.582	1.705	1.607
6.	0.698	0.796	0.821	0.870	0.944	0.919
7.	1.631	1.779	1.901	2.024	2.171	2.098
8.	1.852	2.000	2.049	2.221	2.343	2.417
9.	1.680	1.779	1.926	2.000	2.196	2.073
10.	1.950	2.073	2.270	2.368	2.564	2.343
11.	3.350	3.620	3.841	4.136	4.381	4.480
12.	2.908	3.105	3.301	3.571	3.768	3.817
13.	3.792	4.038	4.332	4.676	4.922	4.946
14.	4.160	4.455	4.725	5.069	5.413	5.462
15.	8.531	7.942	6.616	5.585	5.683	5.658
16.	12.116	11.994	11.552	11.674	11.134	11.085

pressures shown in psia

barometer = 29.336 in. Hg

Table II

Static Pressures in the Test Cavity

L = 1.000 in.

tap #	P_o (psig)					
	60	65	68	70	75	80
1.	1.715	1.739	1.837	1.862	2.009	2.107
2.	1.223	1.297	1.322	1.420	1.469	1.616
3.	1.371	1.469	1.567	1.567	1.665	1.960
4.	1.469	1.543	1.567	1.665	1.764	1.960
5.	1.862	1.911	2.009	2.107	2.255	2.353
6.	0.683	0.757	0.781	0.831	0.880	0.880
7.	1.469	1.592	1.665	1.665	1.813	1.911
8.	1.665	1.739	1.813	1.862	2.009	2.058
9.	1.616	1.715	1.764	1.813	1.960	2.058
10.	1.616	1.715	1.715	1.715	1.911	2.009
11.	2.893	3.041	3.188	3.237	3.483	3.679
12.	3.384	3.581	3.728	3.777	4.023	4.317
13.	3.875	4.121	4.268	4.416	4.612	4.907
14.	4.023	4.170	4.317	4.416	4.710	5.005
15.	9.621	9.179	7.517	6.626	5.152	5.496
16.	12.617	12.666	12.323	11.979	12.077	11.046

pressures shown in psia

barometer = 29.204 in. Hg

Table III

Static Pressures in the Test Cavity

L = 0.667 in.

tap #	P_o (psig)					
	60	62	65	70	75	80
1.	1.776	1.776	1.874	1.972	2.071	2.267
2.	1.187	1.187	1.481	1.383	1.432	1.530
3.	1.383	1.432	1.481	1.678	1.678	1.874
4.	2.021	2.120	2.169	2.365	2.463	2.660
5.	2.414	2.463	2.562	2.807	2.758	3.102
6.	0.745	0.745	0.745	0.843	0.941	1.039
7.	1.530	1.579	1.579	1.825	1.874	2.120
8.	1.678	1.776	1.776	1.923	2.021	2.169
9.	1.629	1.727	1.727	1.972	1.972	2.218
10.	3.593	3.691	3.888	4.526	4.084	5.263
11.	3.740	3.789	3.937	4.281	4.379	4.821
12.	3.347	3.446	3.593	4.084	3.937	4.575
13.	3.642	3.740	3.839	4.231	4.231	4.772
14.	4.526	4.525	4.821	5.165	5.066	5.803
15.	9.976	9.339	8.750	6.982	5.312	5.901
16.	12.629	12.482	12.138	12.089	11.451	11.107

pressures shown in psia

barometer = 29.028 in. Hg

Table IV

Static Pressure Variation in the Test Cavity

L = 0.333 in.

tap #	P_o (psig) 53	55	60	65	70	75	80
1.	1.573	1.622	1.819	1.868	2.015	2.163	2.261
2.	1.082	1.131	1.180	1.279	1.377	1.426	1.573
3.	1.917	2.015	2.163	2.310	2.457	2.654	2.801
4.	2.359	2.408	2.506	2.703	2.899	3.047	3.243
5.	2.654	2.752	2.948	3.096	3.341	3.587	3.783
6.	0.689	0.738	0.738	0.837	0.886	0.886	0.935
7.	1.328	1.426	1.475	1.573	1.721	1.819	1.966
8.	1.622	1.573	1.721	1.819	1.966	2.064	2.212
9.	2.899	2.948	3.145	3.390	3.636	3.832	4.127
10.	2.997	3.047	3.390	3.489	3.832	4.029	4.225
11.	2.654	2.703	2.948	3.145	3.341	3.538	3.734
12.	2.899	2.997	3.145	3.390	3.587	3.783	4.029
13.	3.292	3.292	3.489	3.783	3.980	4.274	4.569
14.	9.382	8.645	6.042	4.274	4.569	4.815	5.060
15.	11.887	11.739	10.806	10.020	9.529	9.235	7.417
16.	13.704	13.556	13.114	12.869	12.672	12.379	12.034

pressures shown in psia

barometer = 29.216 in. Hg

Table V

Static Pressure Variation in the Test Cavity

L = 0.000 in.

tap #	45	50	55	60	65	70	75	80
1.	1.434	1.483	1.581	1.729	1.827	1.974	2.072	2.220
2.	1.336	1.434	1.581	1.729	1.876	1.974	2.122	2.269
3.	2.023	2.220	2.367	2.564	2.711	2.907	3.104	3.300
4.	2.023	2.171	2.367	2.514	2.613	2.809	3.006	3.104
5.	2.760	3.055	3.251	3.497	3.742	4.028	4.282	4.528
6.	0.599	0.599	0.697	0.746	0.746	0.845	0.894	0.943
7.	1.188	1.238	1.336	1.483	1.483	1.680	1.778	1.876
8.	2.564	2.760	2.907	3.202	3.349	3.595	3.791	3.988
9.	2.514	2.711	2.907	3.104	3.300	3.595	3.791	4.037
10.	1.680	1.729	1.876	2.023	2.072	2.220	2.318	2.367
11.	2.220	2.318	2.514	2.711	2.907	3.006	3.202	3.398
12.	6.149	2.662	2.858	3.055	3.202	3.398	3.595	3.840
13.	9.046	7.524	4.037	3.644	3.840	4.135	4.332	4.626
14.	11.600	10.421	9.095	8.457	7.180	4.970	4.528	4.724
15.	13.466	12.680	12.140	11.796	11.109	10.421	10.028	9.194
16.	14.203	13.957	13.663	13.368	12.975	12.828	12.582	11.993

pressures shown in psia

barometer = 29.134 in. Hg

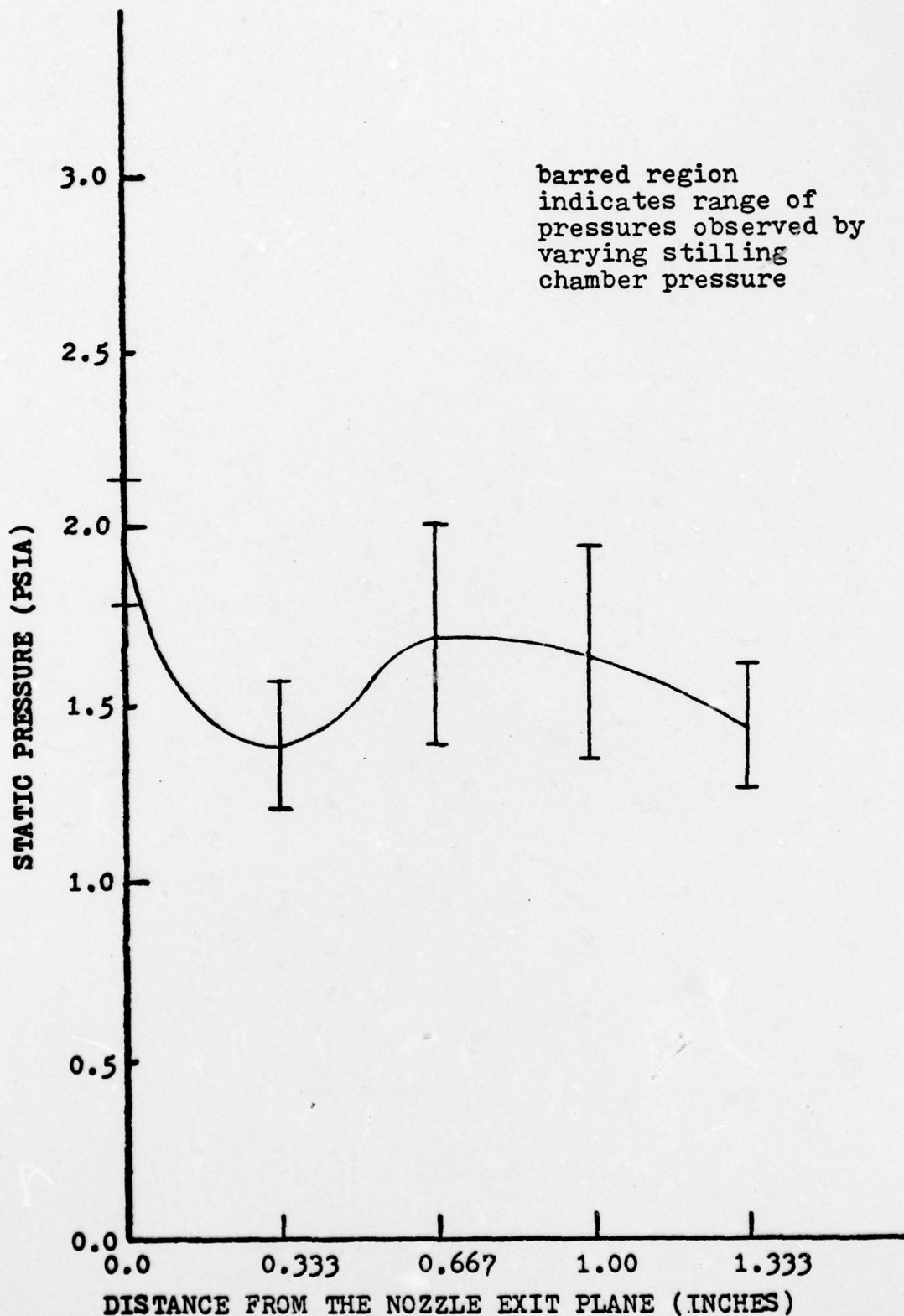barred region indicates range of pressures observed by varying stilling chamber pressure

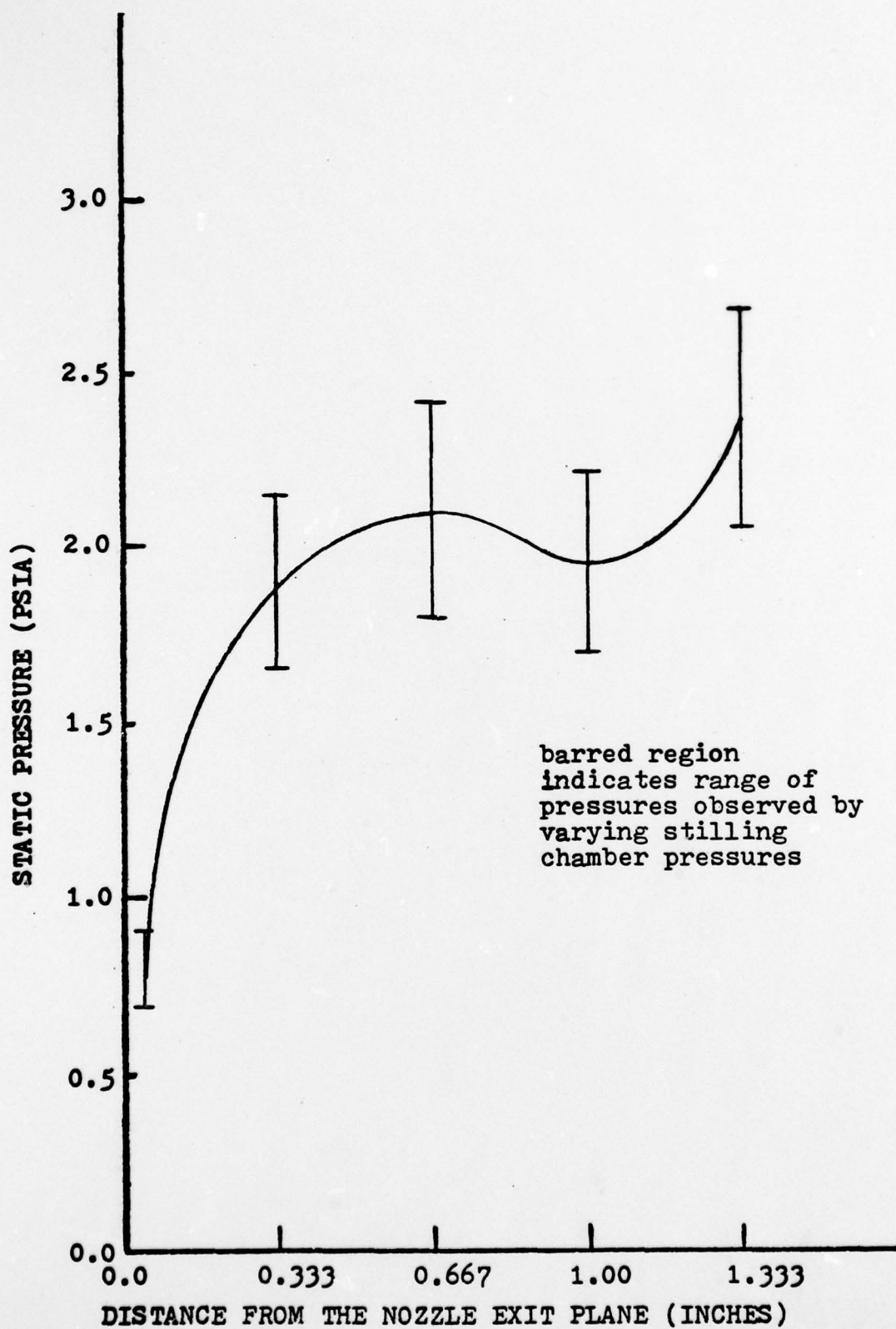Fig. 21. Nozzle Flow Static Pressure Variation, L = 1.333 in.

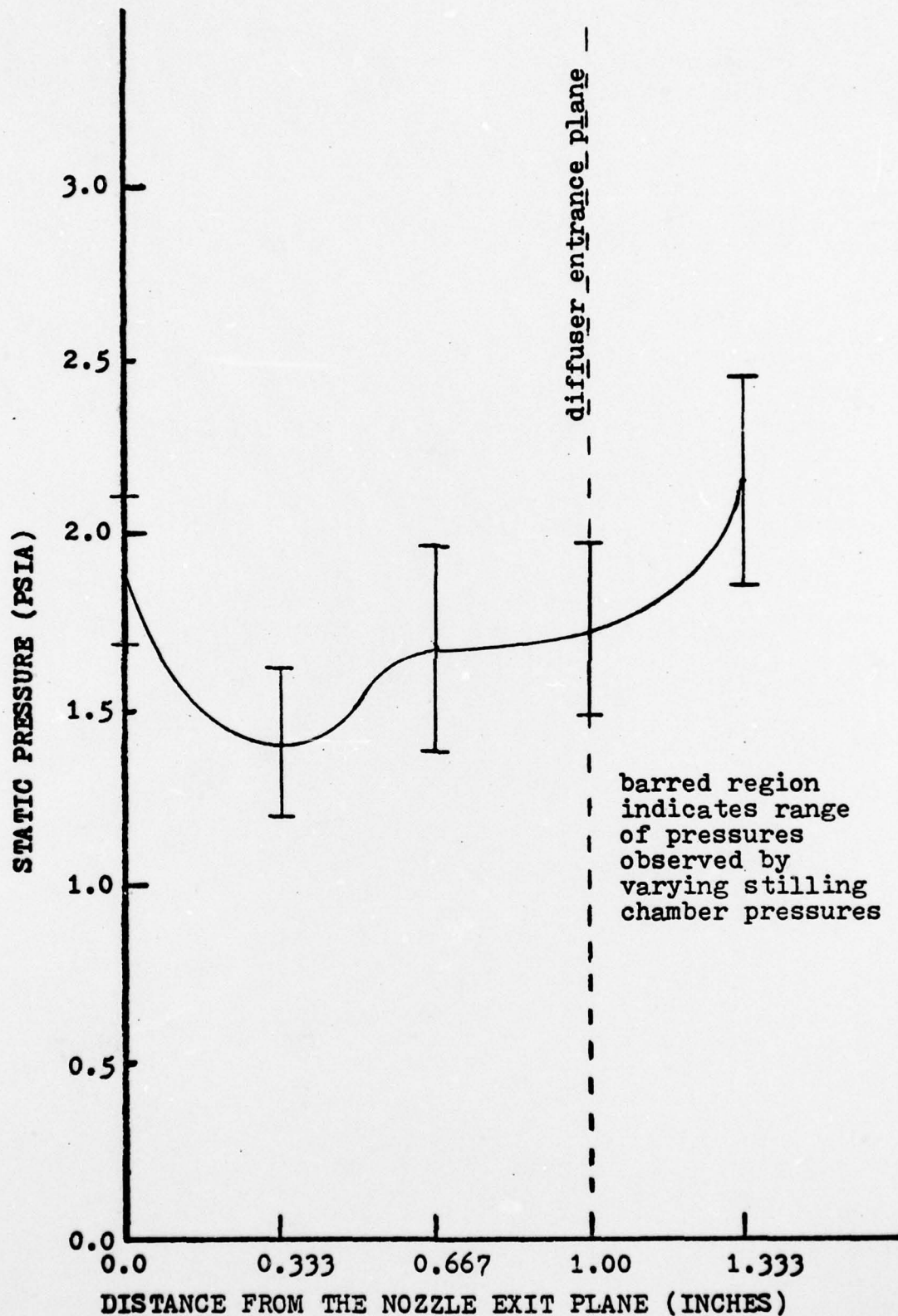**Fig. 22.** Wake Flow Static Pressure Variation, L = 1.333 in.

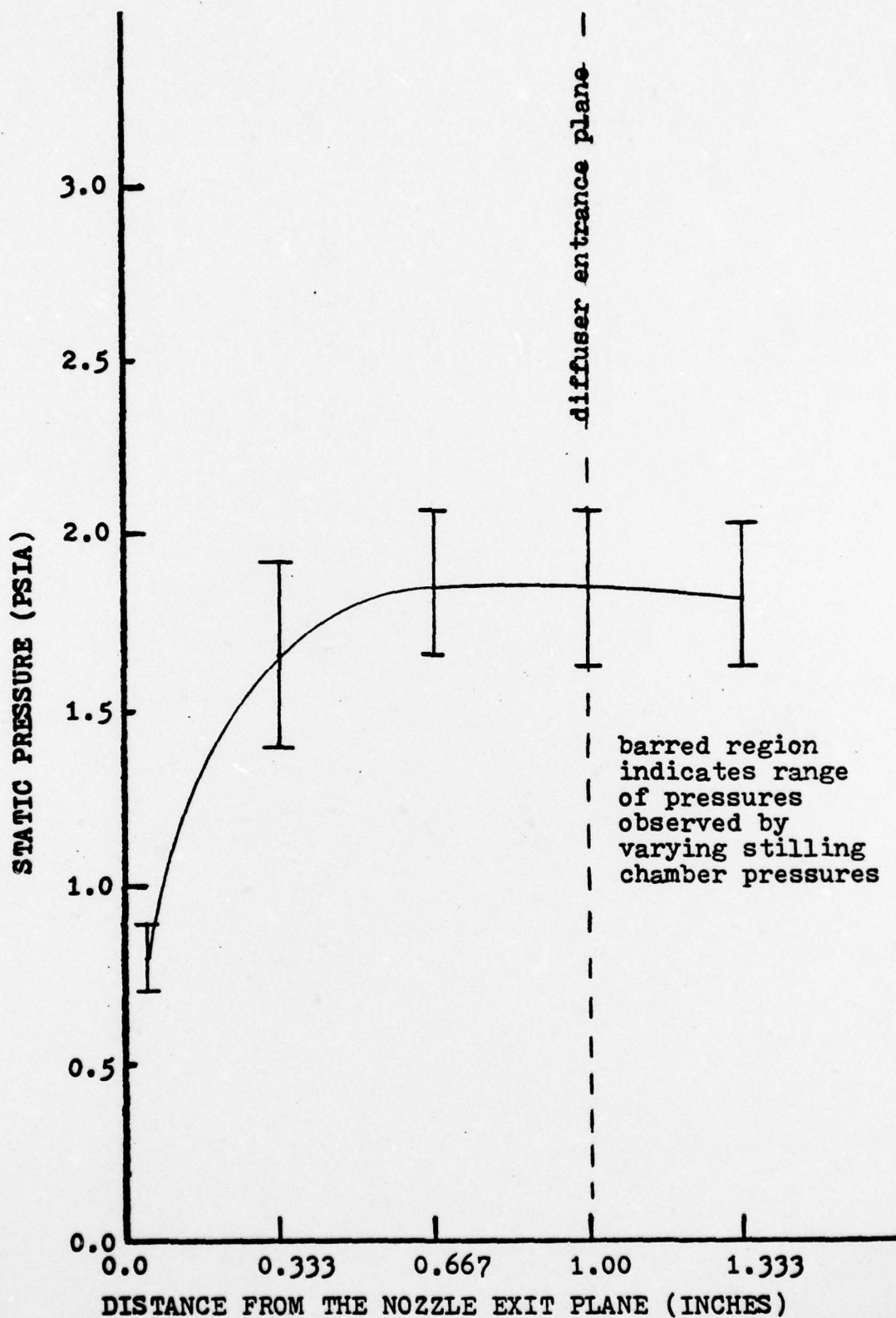Fig. 23. Nozzle Flow Static Pressure Variation, L = 1.000 in.

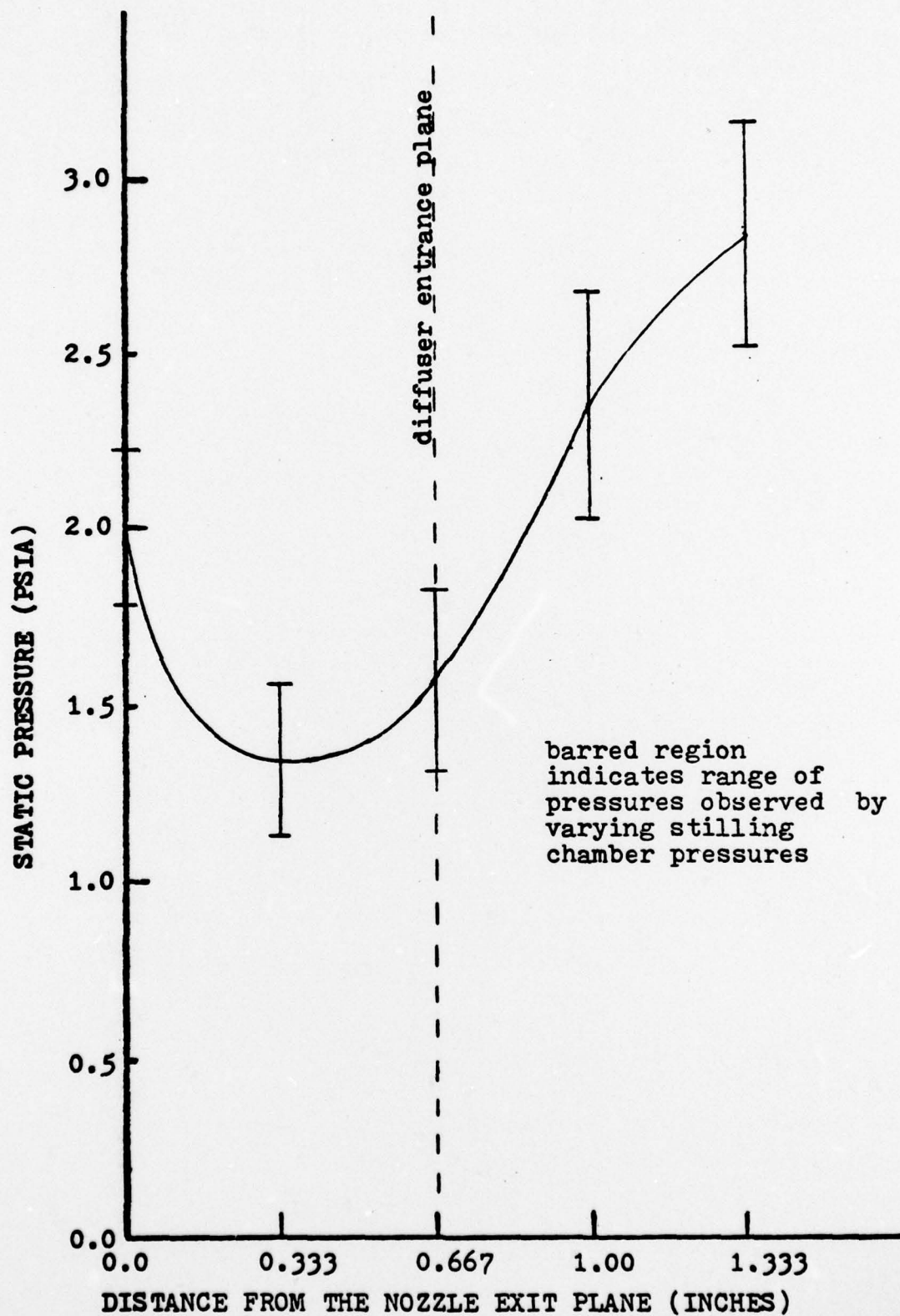Fig. 24. Wake Flow Static Pressure Variation, L = 1.000 in.

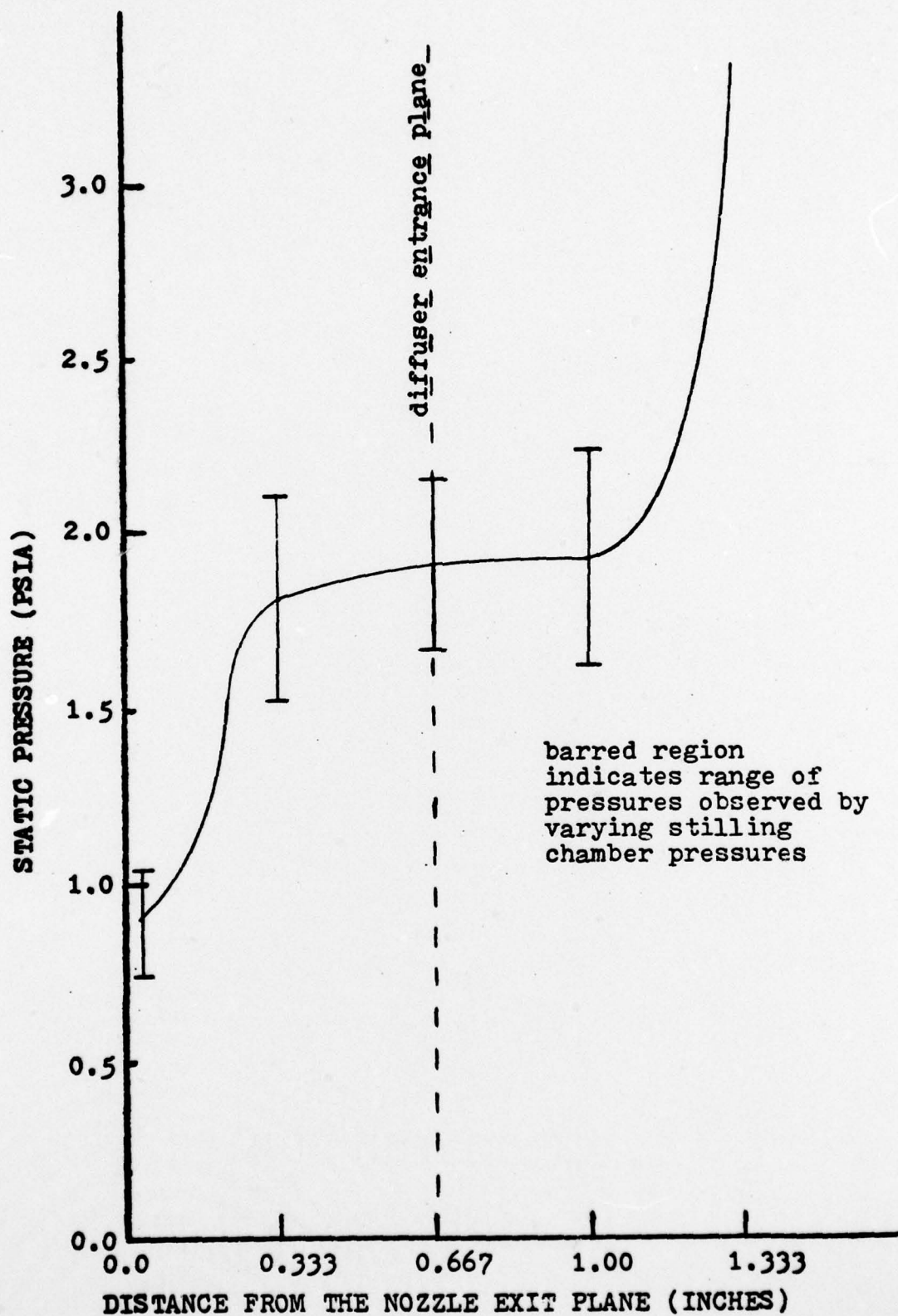Fig. 25. Nozzle Flow Static Pressure Variation, L = 0.667 in.

Fig. 26. Wake Flow Static Pressure Variations, L = 0.667 in.

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Vita

Jeffrey L. Kiner was born 6 August 1947 in Prophetstown, Illinois, the son of Roland D. and Lois M. Kiner. He graduated from Prophetstown High School in 1965. He graduated from the University of Illinois in 1970 with a Bachelor of Science degree in Aeronautical and Astronautical Engineering. He completed navigator and electronic warfare training at Mather AFB, California, and was assigned to flying in EB-66 aircraft at Korat Royal Thai Air Force Base, Thailand. He entered the Air Force Institute of Technology from an assignment as Remote Control Officer in DC-130 aircraft at Davis-Monthan AFB, Arizona. His assignment upon completion of the AFIT program is at Kirtland AFB, New Mexico, in the Air Force Weapons Laboratory (AFSC).

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Pressure measurements and schlieren photographs were used to study the flow characteristics in a two-dimensional multiple-nozzle multiple-diffuser assembly. The assembly consisted of 29 full nozzles with a half nozzle at each end of the array. The contoured nozzles were designed for an ideal Mach number of 3.23 . Fourteen axial diffuser vanes provided 15 diffuser passages. Flow characteristics were studied at five positions of the diffuser entrance plane with respect to the nozzle exit

plane. Air at 80F and a maximum of 118 psig was passed through the nozzles into a constant area region then through the diffusers to ambient conditions. The test cavity start and unstart pressures decreased as the diffuser entrance plane approached the nozzle exit plane. A diffuser leading edge in the immediate vicinity of a major alternate nozzle trailing edge shock intersection resulted in a flow instability during cavity start. This instability resulted in a subsonic wake in the test cavity after cavity start.